Tide-Surge Interactions in the Dutch North Sea, Based on Historical Data from 1960 to 2015.

Max Roebeling

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Utrecht University

Abstract

Storm surges are on the same order of magnitude as tide in terms of short term water level variations. Their periods can range from a couple of hours to 2-3 days. Surges interact with local basin morphology, just like tides do. Therefore, surges and tides can interact, called tide-surge interactions. These interactions can take on many forms, the most researched one being the increase in peak water level for flood risk assessment.

Most studies focused on tide-surge interactions in physical models. The resulting water levels were then fitted against tide gauge data of the observed water level. Though models have gotten better, they still underestimate the observed water levels. Other studies based on historical data have focused on finding methods to quantify storm surges. Some regional studies have also been performed, finding the importance of taking regional morphology into account, like intertidal mudflats in estuaries. These studies have also stated the importance of large tide gauge networks to investigate tide-surge interactions. Other studies in the British North Sea and Thames yielded that peak surges tend to fall earlier than the high tide. What is lacking, is a detailed study of tide-surge interactions of the Dutch North Sea based on historical tide gauge data.

The Dutch coast has a lot of variation on a relatively small scale. It consists, among others, partially of estuaries and a marginal sea. Regional patterns in the tide-surge interaction can therefore be very important for model predictions. This study has therefore focused on three different regions within the Dutch coast: along the Dutch coast line, the Westerschelde estuary and the Wadden Sea. Using Python for data analysis, observed water level data from the Gesla3 dataset was compared with astronomic water level data from Rijkswaterstaat. Surges were defined from the observed water level data in two ways: the Godin filter, and the skew surge.

Results show that surges have a larger influence on the peak observed water levels in the Westerschelde estuary and in the Wadden Sea, compared to the Dutch Sea coast line. Furthermore, the surge tends to increase its effect on higher water levels in the Westerschelde further into the estuary, up to Bath. In the Wadden Sea, the tidal basin determines the strength of the surge on the tide. There is no surge effect on the tidal range along the North Sea side of the Wadden Islands and within the Wadden Sea itself. In the Southern part of the Dutch coast and in the Westerschelde estuary, surges have a small influence on the tidal range, but more research on why this happens only in these locations is needed. There is no correlation between the observed timing of the full tidal cycle, due to the influence of surges. For high and low tide, however, surges tend to cause earlier observed high or low tide when compared to the astronomic tide, but this is dependent on the location. In the Wadden Sea, this can be linked with flooding and exposure of intertidal areas due to the surge effect. Observations indicate that earlier high and low tide can often be associated with increased tidal wave speeds, due to rising surge heights. These associations can often be linked with the existence of intertidal areas or mudflats.

1 Introduction

Storms pose a considerable risk to coastal zones. They can produce storm surges, which, depending on the storm, are potentially large water level variations that can interact with the tide. Depending on their timing in the tidal cycle, storm surges can induce large risks for coastal areas and navigation. For the hinterland a large positive storm surge can pose a threat during high tide, while during low tide, a high storm surge can go unnoticed. Negative storm surges (so storm surges which cause lower water levels) can also cause problems if they occur during low tide, as channels can suddenly be too shallow for ships to navigate through. With the challenge of sea level rise, larger surges can become increasingly problematic. Therefore, it is vital to understand the effects of surges on the observed water level.

This paper focuses on tide-surge interactions in the Dutch North Sea, based on historical data from three distinct areas. First, an overview of tides, surges and tide-surge interactions is given.

1.1 Definitions: Tides, Surges and Tide-Surge Interactions

1.1.1 Tides

The daily water level is affected by many different processes, the main one being tides. Depending on the location, tides are deformed and can be enhanced due to resonance, locally this can exceed 10 meters, such as in the bay of Fundy (Pugh, 1987; Godin, 1993). Tides form in the deep ocean by gravitational forces with feedback in tidal dynamics, namely self-attraction and loading (Hendershott, 1972). After formation, tides travel as shallow water waves, as their wavelength can be several hundreds of kilometres long, much longer than the ocean's depths. While travelling, they are deflected by the Earth's Coriolis force, and dissipate when they experience bottom friction in shallow waters by the continental shelve and energy loss by internal tides.

As tides enter the continental shelf, they interact with local basin morphology. The amplitude of the tidal wave will increase due to the sudden change in water depth, as the wave energy needs to be conserved (D. Pugh & Woodworth, 2014). Near the coast, tides deform further as water depth continues to decrease. For instance, at a beach, a wave becomes steeper as it approaches to the shore (see figure 1), which is similar to the tide deforming.

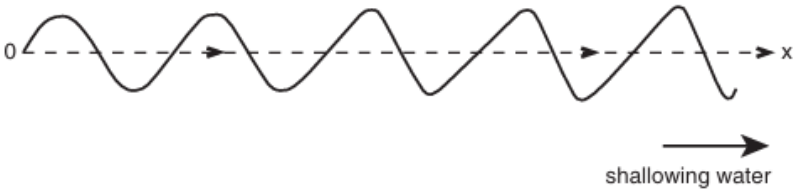

Figure 1: Example of the tidal wave becoming steeper. Figure source: D. Pugh and Woodworth (2014).

The Coriolis effect also influences the tidal wave height, as the propagation direction of the wave is diverted to the right on the Northern Hemisphere. As the tidal wave enters the North Sea basin (figures 4 and 5), due to the Coriolis effect, the water of the tidal wave is pushed towards the coast (right) as the wave propagates through the basin. This phenomenon results in higher water levels at the coast compared to the sea ward side during high tide. Conversely, on the opposite side of the basin, water is pulled away from the coast in effect, leading to a lower low tide there. This mechanism creates a Kelvin wave (see figure 2), which explains the occurrence of higher high tides and lower low tides.

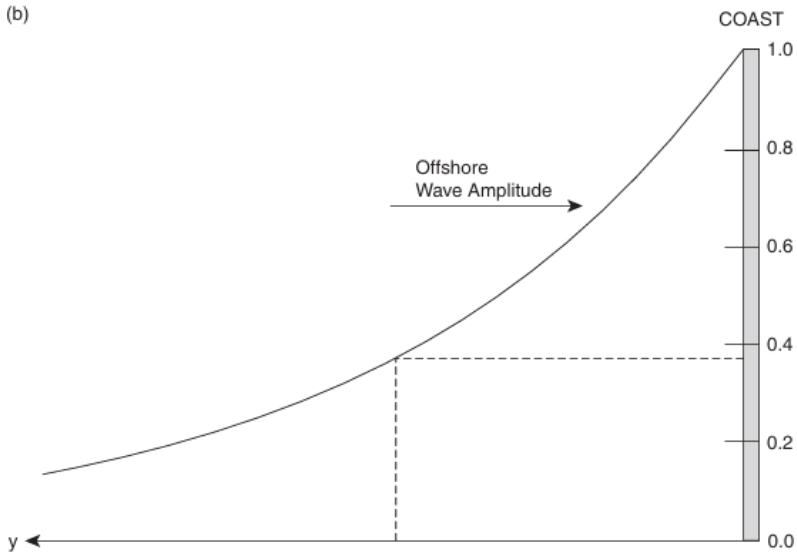

Figure 2: Cross section of a simplified Kelvin wave. Figure source: D. Pugh and Woodworth (2014).

Since the wave will cause a higher water level on one side of the basin and a lower water level on the other, there is a line on which there is no water level change. Since the tide is a continuous wave, once the wave has travelled fully through the basin, these lines of no water level change intersect, leading to a single point where no water level change is present: the amphidromic point (see figure 3). In an ideal system with no energy loss, this amphidromic point stays in the centre of the basin. However, this point shifts when the reflected wave has experienced energy loss (see figure 3) (D. Pugh & Woodworth, 2014). Since the North Sea is not a rectangular basin, local characteristics and energy loss matter for the position of the amphidromic point. The North Sea has several amphidromic points (see figures 4 and 5).

The further an area is from an amphidromic point, the larger the tidal range (the difference between high and low tide). Changes in strength of the tide shift the amphidromic point accordingly, resulting in changes of the tidal range and water levels. At the Dutch coast, a *stronger* wave would lead to amphidromic points shifting *away* from the coast, thus resulting in *higher* water levels.

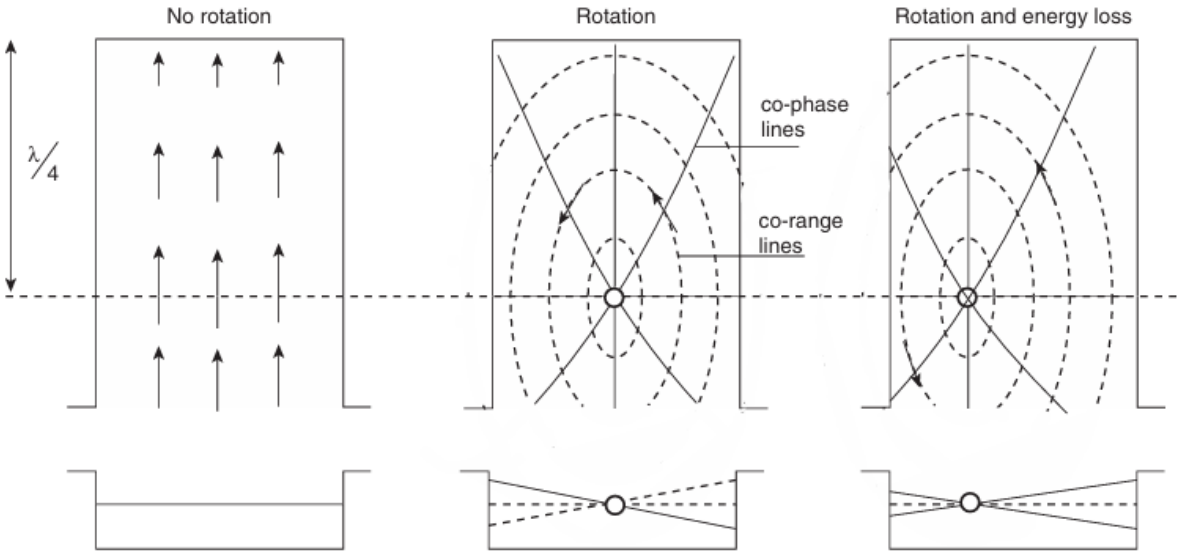

Figure 3: Example of amphidromic points in a schematic basin. Top three figures show an top view of the basin, while the bottom 3 figures show a cross sectional overview. Co-range lines indicate equal water levels and the co-phase lines where the phase of the tide matches. Figure source: D. Pugh and Woodworth (2014).

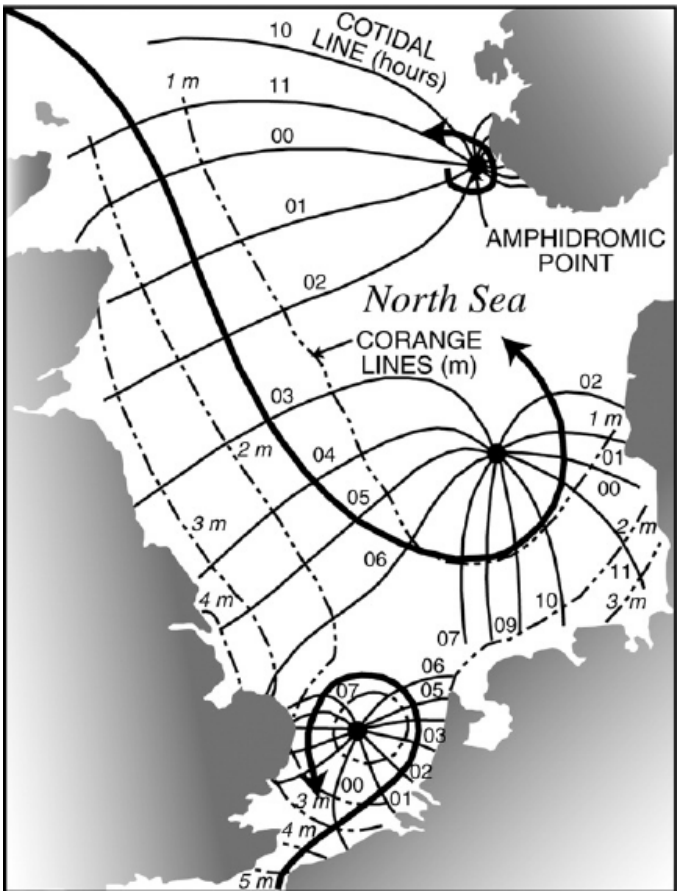

Figure 4: Amphidromic points in the North Sea. Dotted lines are the co-tidal range lines, the filled lines are co-tidal phase lines. Figure source: Kvale (2006).

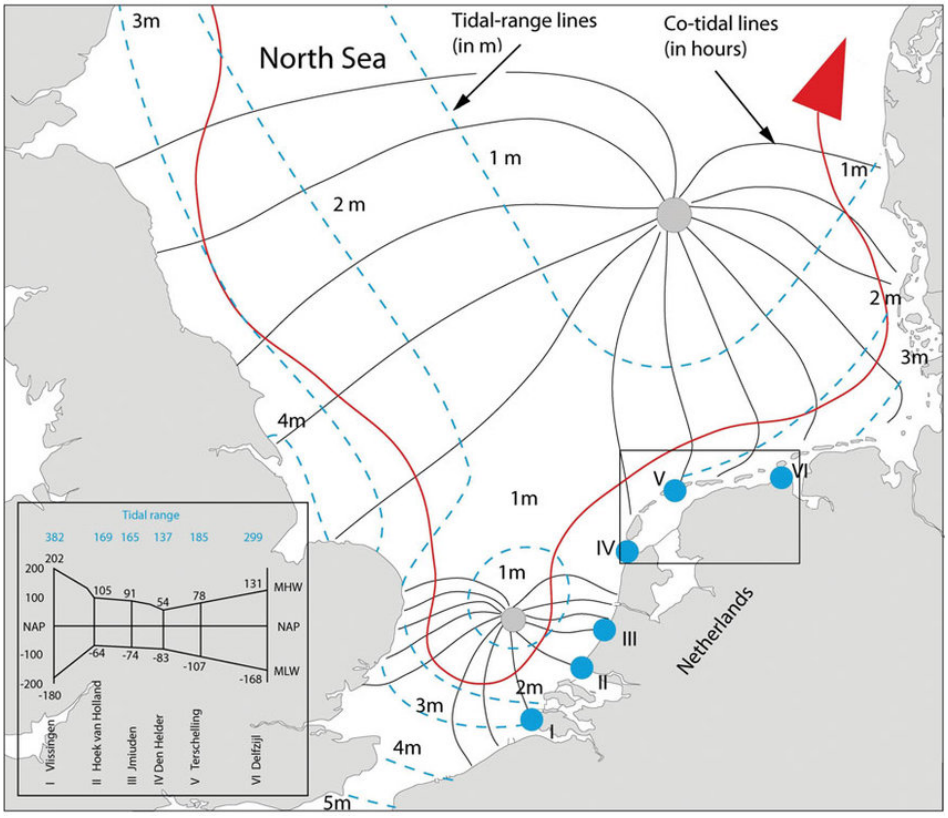

Figure 5: Tidal wave propegation through the North Sea. Figure source: Vos and Knol (2015).

Other dynamics that result in new waves form the tidal wave are taken into account when making a prediction of the tide (Parker, 2007). These processes, that occur during every tidal cycle and show a regular wave like pattern, are called tidal constituents. All constituents together form the prediction of the tide: the astronomic tide. Important to note is that in the astronomic tide, weather effects are not taken into account, as these changes in water level are more of a chaotic nature, instead of a clear daily occurring wave. The astronomic tide is therefore really good for baseline water level fluctuations. However, as shown in figure 6, the observed water level is often different compared to the astronomic tide.

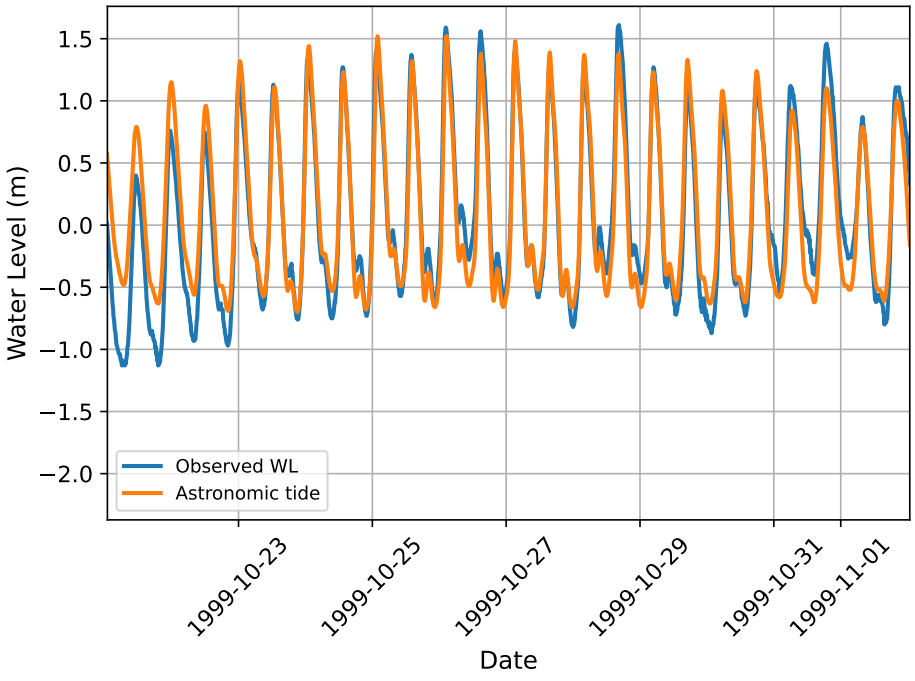

Figure 6: Example of the observed water level being different from the astronomic tide.

1.1.2 Surges

Apart from tides, storm surges, are among the largest influences of shorter time scale water level fluctuations (D. Pugh & Woodworth, 2014; Idier et al., 2019). Figure 7 shows that surge in itself can be of the same order of magnitude as the tide. They result from long lasting wind stresses and low atmospheric pressure and can be classified as a long shallow water waves, just like tides (Idier et al., 2019). Their wave periods can range from a couple of hours to 2-3 days (Flather, 2001) and can quickly cause water levels to rise. For example, in the Southern North Sea where the water depth is roughly 30m, a wind speed of $22m/s$ could create a surge level of 0.85m. With a wind speed of $30m/s$, the surge water level would be 1.6m high (Ponte et al., 1991). In the most extreme cases in the North Sea, like in the 1953 storm, this can even rise up to 2-3m (Wolf & Flather, 2005).

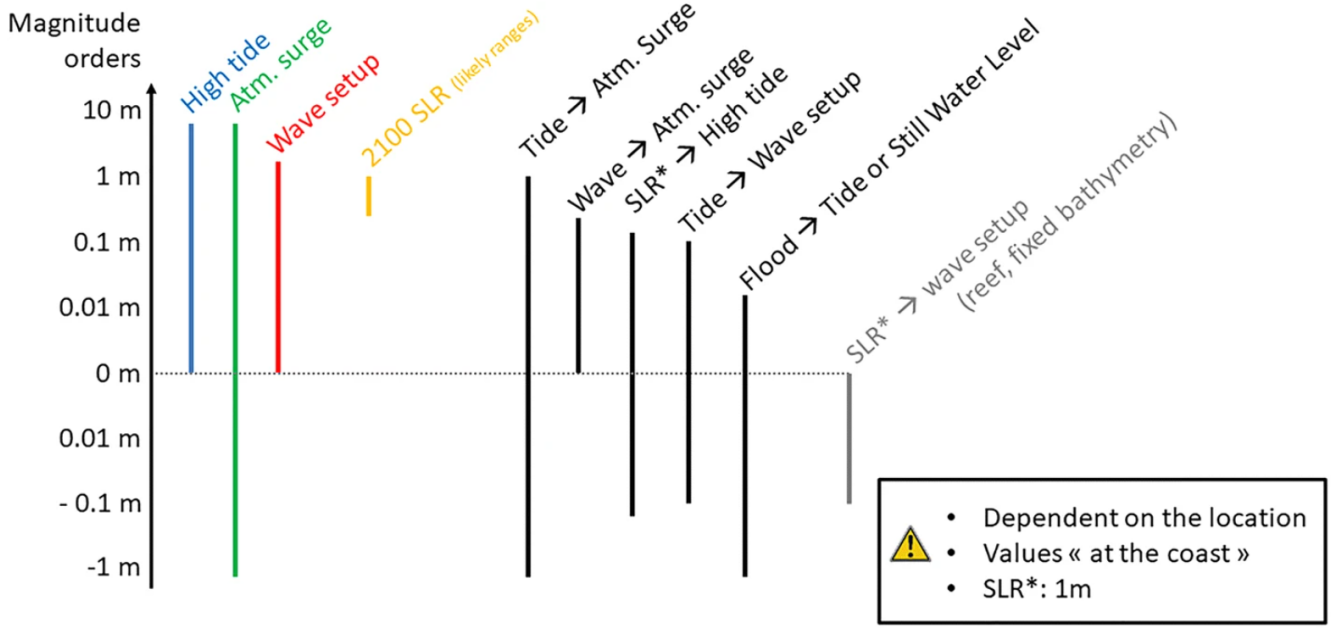

Figure 7: Orders of magnitude on sea level variations. Figure source: (Idier et al., 2019).

Though extremes like the 1953 storm are important to study, smaller storm surges can have a significant effect on the water level as well. Under less extreme conditions, storms surges of only a couple of decimetres can be of greater interest than other water level fluctuations, like seiches or coastal waves (D. Pugh & Woodworth, 2014). Furthermore, a surge in one location may differ from a surge in another location. There are situations, due local coastal dynamics, a positive surge occurs at one location, and a negative surge occurs at a location nearby (Pousa et al., 2013).

Generally, storm surges are classified, in three different categories: forerunner, primary surge and coastally trapped waves (see figure 8).

When storms occur farther offshore, elevated water levels can already be observed from the tide gauge. These higher waters can reach the shore up to 3 days in advance of the storm landfall. This is called the forerunner (Bui, 2021). Generally the forerunner is not a tall wave, rarely reaching 1m in height in tropical regions (Kennedy et al., 2011), even less at higher latitudes. However, since the forerunner can have a longer period than the tide itself, it generally coincides with at least one high tide, potentially increasing the risk of inundation (Bui, 2021).

As the storm hits the coast, the surge rises rapidly, also known as the primary surge. Note that this is different from seiches. Seiches are higher frequency oscillations during the storm landfall due the formation of a standing wave (Bui, 2021). The primary surge peaks roughly at the same time as the storm hits the coast, and is several times larger than the forerunner. For example, in the case of the 1953 storm in the Southern North Sea, the primary surge was responsible for the 2-3m increase in water levels (Wolf & Flather, 2005).

As the storm winds move further inland, or die out, the winds' stress is relaxed and the surge is released as long waves. These waves oscillate on their own and are thus not a forced wave, but an after effect of the storm. They can occur up to ten days after the storm (Bui, 2021).

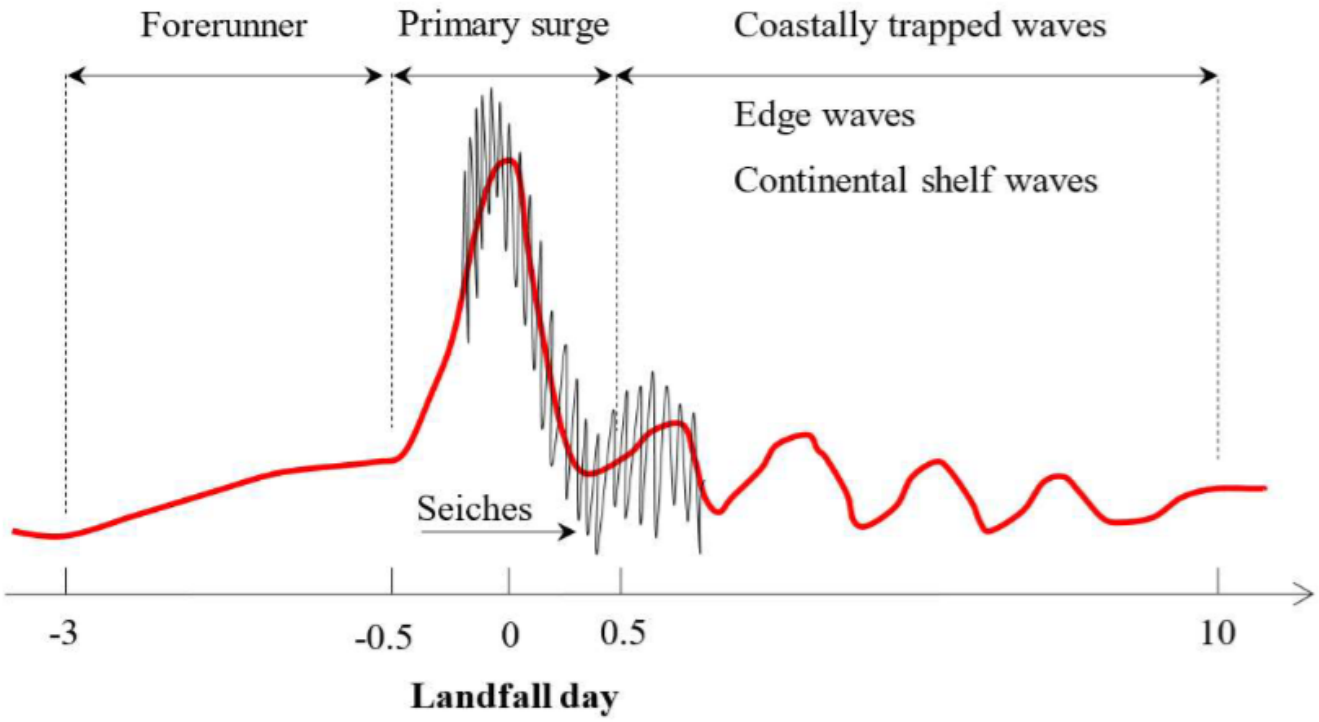

Figure 8: Categories of the storm surge. The red line is the example of the surge. Figure source: Bui (2021).

Any combination of these categories is possible at a location, depending on whether the storm hits the land or not. If the storm does hit the land, then it is likely the tidal signal will reflect water level changes for all three of these general categories. If a storm forms near the coast only the last two categories are likely to occur. If the storm never hits or gets close to land, only the forerunner or coastally trapped waves could end up in the signal.

Furthermore, just like tides, surges can change due to local characteristics, one of the main factors being that surges tend to amplify when water depth increases, which is seen along the Orissa coast in India (Sinha et al., 2008). Some other factors are: fluvial discharge, rainfall and wind set-up (Plüß et al., 2001; Rego & Li, 2010b; Orton et al., 2012). Depending on the location along the Dutch coast, this can have implications for the observed water level. In the Westerschelde for example, river discharge, and the existence of intertidal mudflats can significantly change the way the surge will evolve through the system (van Rijn, 2010).

1.1.3 Tide-Surge Interaction

Since surges are waves, they interact with other waves (Idier et al., 2019), this is called a tide-surge interaction. With the above background we can establish some and literature, we can establish some hypotheses of what will happen when tide and storm surge interact in the Dutch North Sea.

Tide-surge interactions are the strongest interaction when looking at shorter time scale water level variation (ranging from couple of hours to a couple of days) (Idier et al., 2019). Figure 7, shows that tide-surge interactions are the strongest interaction mechanism for water level fluctuations (Idier et al., 2019). As a consequence, higher water levels have been shown to coincide with the larger surges (Flather, 2001; Wolf & Flather, 2005; Idier et al., 2019).

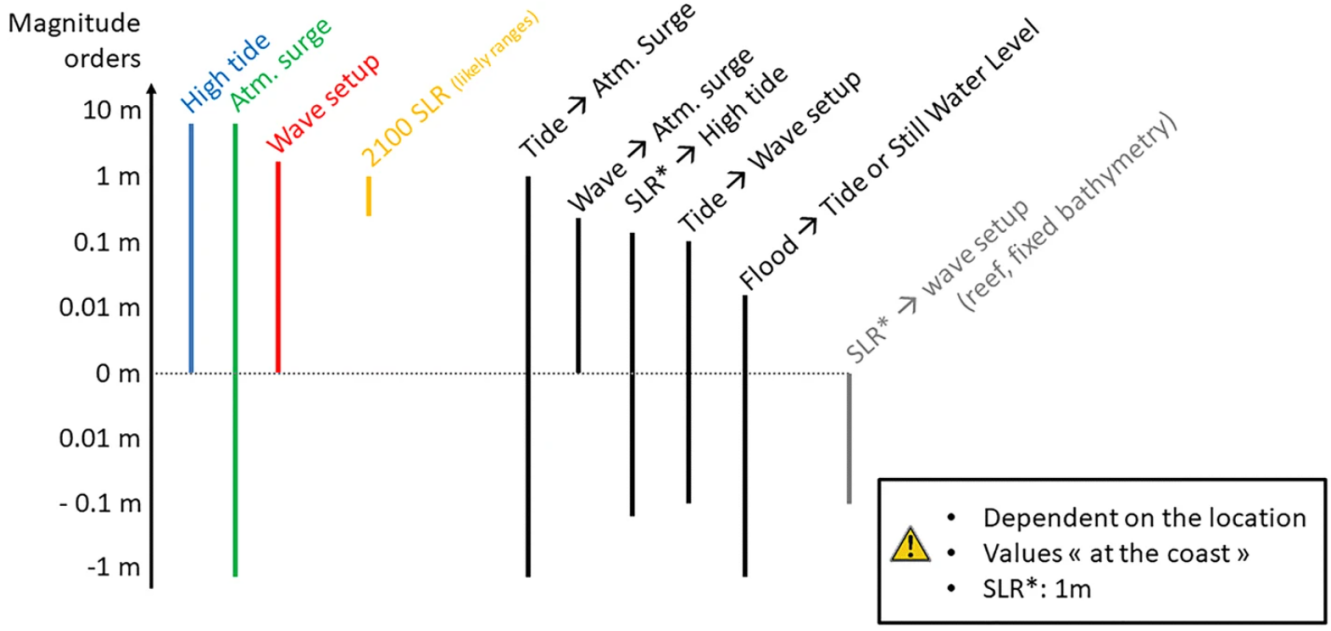

Figure 7 repeat: Orders of magnitude on sea level variations. Figure source: (Idier et al., 2019).

Though higher or lower water levels are largely explained by superposition, other mechanisms that influence the observed signal are put into motion by the tide-surge interaction. When a large positive surge enters the system, the average water levels rise, causing a larger total energy of the incoming wave. How much energy is lost when the tidal wave is reflected, cannot be known with certainty from tide gauge data, but it is expected that the amphidromic points will shift when the surge and tidal wave travel through the system. This will lead to a shift of the amphidromic point to the left on the Northern Hemisphere with a positive surge (D. Pugh & Woodworth, 2014). With figure 4 in mind, a positive surge would cause the Southern amphidromic point to shift to the West, and the center amphidromic point to shift to the North/North-East (thus, away from the coast). This leads to an increase in the tidal range with a positive surge, as the amphidromic points are shifted further away from the coast. If there is a negative surge, we expect the Southern amphidromic point to shift to the East and the middle amphidromic point to the South/South-West, thus leading to a decrease in tidal range.

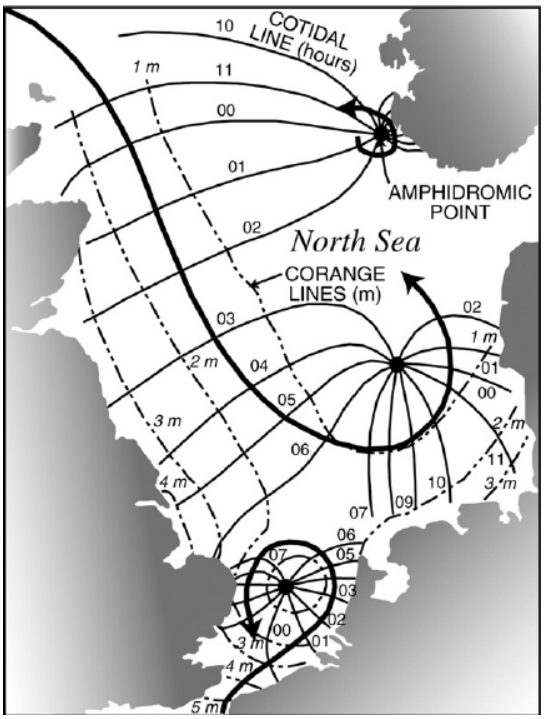

Figure 4 repeat: Amphidromic points in the North Sea. Figure source: Kvale (2006).

Another way in which tides and surges interact is through the changes in water depth. The equation for wave speed in shallow waters is $c = \sqrt{gh}$, where c is the wave celerity (in other words, the wave speed), g the gravitational **constant**, and h the water depth. Therefore, the wave speed is dependent on the water depth. A positive surge leads to a larger water depth for the tide, thus increasing the wave speed of the tide. The other way around is of course also true: a negative surge leads to a slower tidal wave speed (Rossiter, 1961; Horsburgh & Wilson, 2007). This equation also demonstrates that tide-surge interactions are more significant in shallow seas and estuaries (Feng et al., 2021), where the average water depth is much smaller than in an open sea, thus a small increase in depth leads to a relatively large change in wave speed. Vice versa, the tide also oscillates, creating higher and lower water depths, thus wave speeds for the surge can oscillate too. This causes non-linear interactions between the tide and surge. As a consequence we cannot simply superposition the surge water level on the astronomic tide.

Horsburgh and Wilson (2007) have shown that in the North Sea due to the non linear tide-surge interaction, the timing of the peak of large surges often avoids the high tide by a period of 3 to 5 hours. In the Thames, it has been modelled that the peak surge has a tendency to fall on the rising tide instead of other moments in the tidal cycle. Prandle and Wolf (1978) for example, modelled for the Thames several inputs on the sea ward side in order to predict which tide-surge interactions explain observed water levels in the river. They found that surges in the Thames tend to fall on the rising limb of the tidal cycle, irrespective of the phase relation between the storm surge and tide in the northern North Sea. They also showed that the quadratic friction term is the leading factor for this phenomenon. Another model study by Rego and Li (2010a) found that for the Louisianna-Texas coast, non-linearity of the tide-surge interaction is largest when the storm landfalls during low tide, followed by landfalls during high tide and lastly land falls during midebb and midflood. This shows the importance of the timing of the surge.

Regional based studies have taught us several things about tide surge interactions. A paper by Idier et al. (2012) looked at tide-surge interactions in the English channel and showed that surges tend to fall on the rising tide. Furthermore, they used the MARS model to investigate the tide-surge independence, and found that further along the channel to the East, the surge-tide dependency increased slightly. A study in Aotearoa, New Zealand, by Costa et al. (2023) found that the strongest tide-surge interactions occurred in inner estuarine locations, which was correlated with the intertidal area. The authors also stated the importance of an extensive tide gauge network to observe long term trends in estuarine environments. Given that in the Dutch coastal system we have both the Westerschelde estuary and the Wadden Sea with intertidal areas, these regions likely show different patterns in tide-surge interactions than along the coast of the North Sea.

There is some dispute on when surges tend to fall. Williams et al. (2016) for example, have shown that any surge can occur during any moment in the tidal cycle. As this is a larger scale study, taking tide gauge data from the Netherlands, the UK, the US and Ireland, it is likely that this is more of a general pattern and that local basin characteristics cause the tide-surge interaction to have different patterns.

Though small, model studies for the Dutch coast, like the study of Sembiring et al. (2015), show that models tend to underestimate surge elevations when looking at flood risks. Consequently, some mechanisms are not yet fully understood, which is essential for improving model predictions.

Therefore, the present paper aims to study the tide-surge interactions in the Dutch North Sea, based on historical data. As locational/regional patterns are important for surges (Pousa et al., 2013), this paper focusses on three areas, the first one being along the Dutch coast. As the importance of interactions in estuarine environments has been stated in several studies (Rego & Li, 2010a; Lyddon et al., 2018; Costa et al., 2023) this study will also investigate tide-surge interactions the Westerschelde estuary. Given the importance of intertidal areas for tide-surge interactions (Costa et al., 2023) tide-surge interactions will be studied in the Wadden Sea as well.

1.2 Study Area

As already indicated, this study will focus on the tide-surge interactions in the Dutch North Sea, focussing on three smaller sub-areas (or: regions), namely: 1. North Sea (along the Dutch coast, in the actual North Sea); 2. Westerschelde; and 3. Wadden Sea (see figure 9).

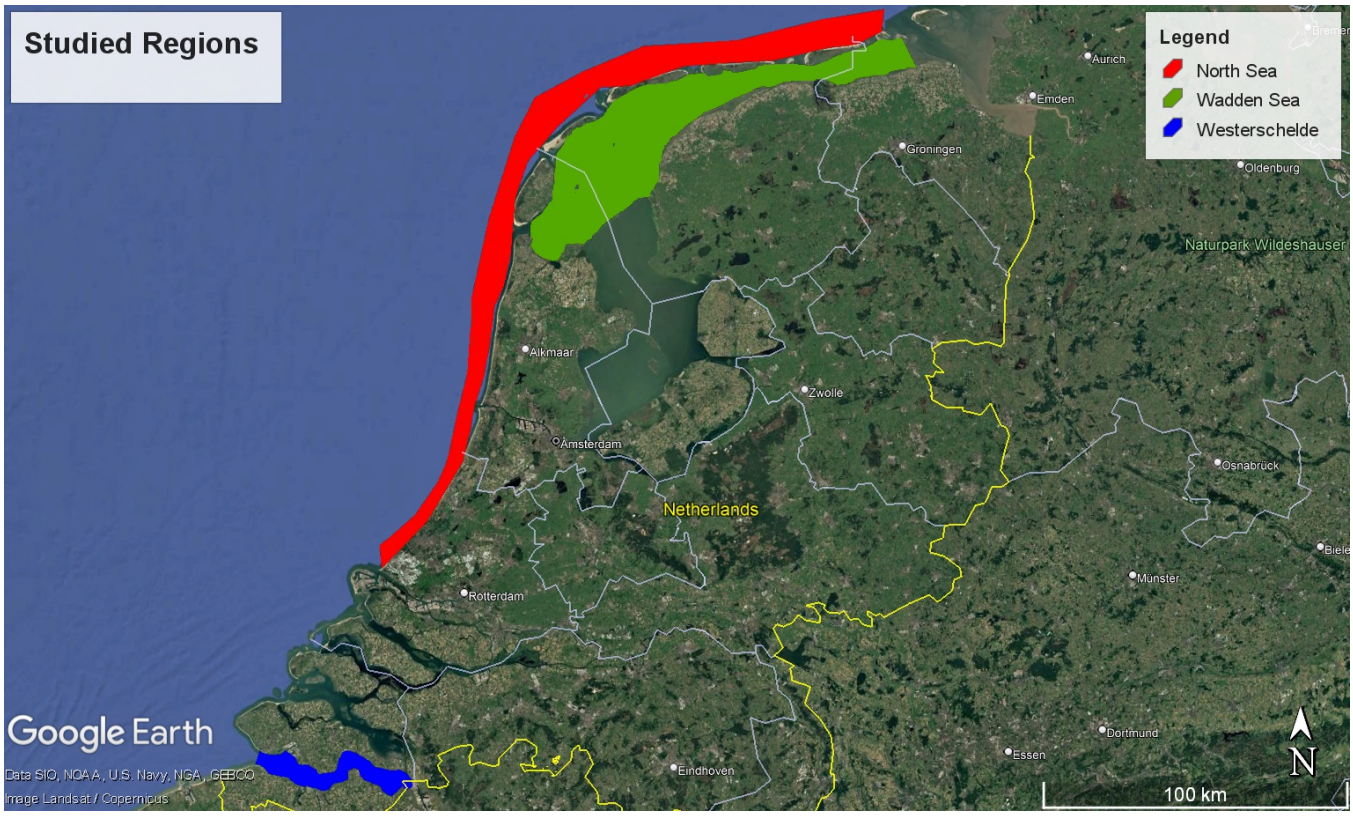

Figure 9: Studied areas in the North Sea. Picture source: "Google Earth Pro" (2025)

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The Wadden Sea and Westerschelde have an important characteristic which controls the average water depth, namely the existence of intertidal areas and intertidal mud flats, respectively.

The Wadden Sea consists for a about 50% of intertidal areas (Compton et al., 2013) (see figures 10 and 11). These areas fall dry about twice per lunar day during low tide. Since wave speed can be approximated to $\sqrt{gh}$ in shallow waters, these intertidal areas play an important role for controlling wave speeds when flooded during storms. For example, when the intertidal area floods during low tide due to a storm, the average water depth *decreases* or stops to increase as the area floods, therefore leading to smaller changes in wave speeds.

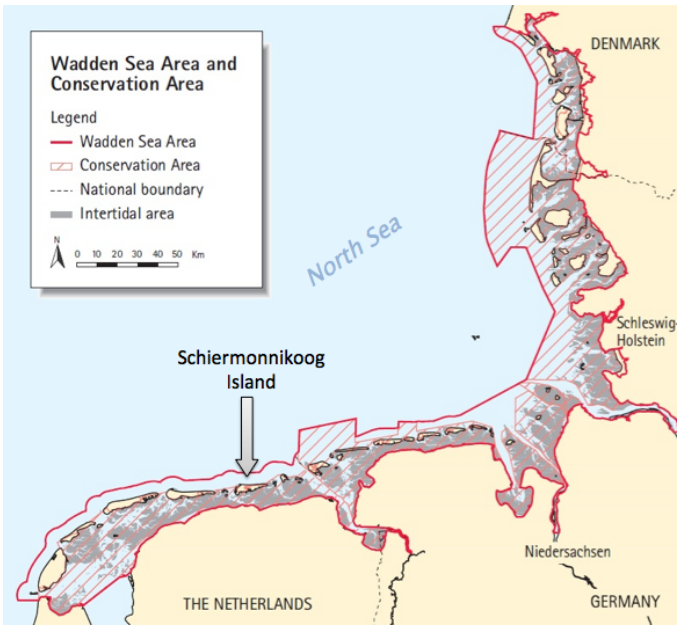


Figure 10: Wadden Sea intertidal areas. Figure source: "Common Wadden Sea Secretariat — Wadden Sea" (n.d.).

Further more, the Wadden Sea consists of several tidal basins. Figure 11 shows the Wadden Sea basins and intertidal areas in more detail. It is known that the tide generally tends to stay within each of the tidal basins (Stanev et al., 2003). However, with surges, at least during high tide, there exists the possibility of basin overflow, creating interactions of the tide between basins as well.

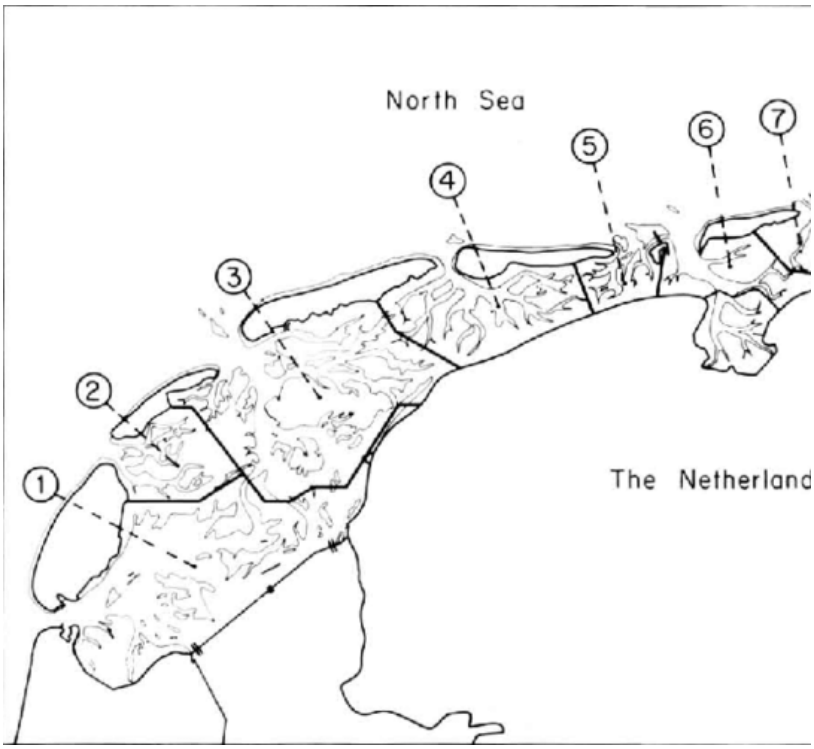


Figure 11: Tidal basins of the Wadden Sea. The black lines indicate the boundaries of where the tide goes. Every inlet therefore has its own tidal basin. The grey lines show where the intertidal areas are present. Figure source: Bergman et al. (1989).

The Westerschelde exists for a large part of intertidal mud flats, which flood during spring tide (Schepers et al., 2018). These mud flats play a similar role as intertidal areas, as they control the average water depth. Figure 13 explains how the tidal wave speed is affected by the flooding of intertidal mud flats.

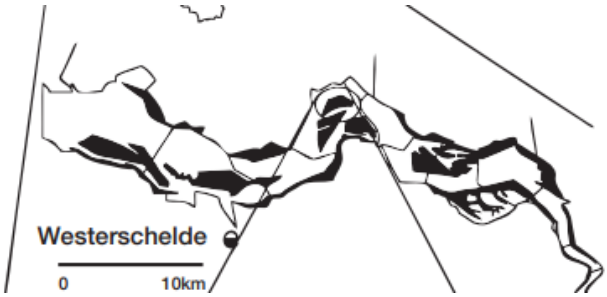


Figure 12: In black, the intertidal mudflats of the Westerschelde. Figure adapted from Wilson et al. (2005).

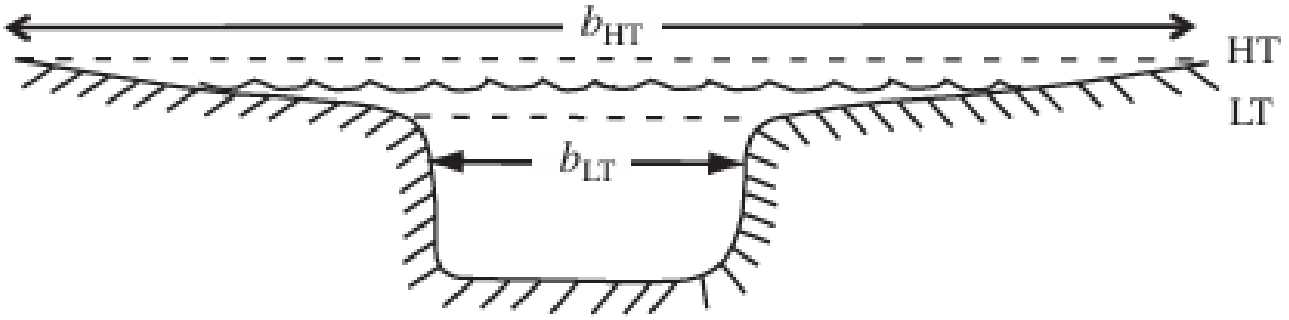


Figure 13: Schematic cross-sectional overview intertidal mudflats flooding control on wave speeds. When the tidal wave only travels through the channel at width b_{LT}, any water on top directly increases the water depth and thus the wave speed. However, at b_{HT} when the intertidal mud flats get flooded, the average depth decreases due to the larger surface area. Figure source: Pethick (1980).

Along the coast in the North Sea these intertidal areas/mudflats do not exist, therefore, an increase in water level due to a positive surge leads to deeper waters. But since Rossiter (1961) and Horsburgh and Wilson (2007) stated that the wave speed is more effected in shallow seas and estuaries, the North Sea might be less susceptible to relatively small water level changes, as it is relatively deep compared to the Wadden Sea and Westerschelde.

1.3 Research Questions

This paper will focus on the following main research question: **What are the tide-surge interactions in the Dutch North Sea?** To answer this question, the following three sub-questions will be examined.

1.3.1 In the Dutch coastal waters, what influences do tide-surge interactions have on the observed water levels and tidal range and where is this interaction stronger?

This question researches where storm surges have a larger influence on the observed water level. Furthermore, given the expectation that amphidromic points tend to shift with storm surges, it is expected that tidal ranges should also be change according to strength of the storm surge. As surges interact with the basin's morphology, some locations might experience a stronger surge influence on the observed water level or tidal range.

1.3.2 What are the shifts in timing of the observed water level for the full tidal cycle compared to the astronomic tide, depending on the location and surge height?

Several studies, like Prandle and Wolf (1978) and Horsburgh and Wilson (2007) Prandle and Wolf (1978) have found that in the Thames river, peak storm surges usually tend to occur during the rising limb of the predicted tide. It is therefore interesting to know whether that will effect the timing of the tidal cycle. Indeed, Horsburgh and Wilson (2007) showed that in some situations surges can arrive more than four hours earlier than the next high tide.

1.3.3 How do surge heights affect tidal wave speeds when looking at different surge heights, depending on the region?

Given that for shallow waters, wave speed can be written as $c = \sqrt{gh}$, positive surges should lead to higher wave speeds and negative surges to lower wave speeds (Flather, 2001). We can fill in this equation with the average water

depth of the North Sea, Wadden Sea and Westerschelde and add and subtract the 1953 surge of 2-3m (Wolf & Flather, 2005) on top of it to see what wave speeds we may expect (see table 1).

Sub-Area (Region)	Average Depth (m)	Expected Wave Speed (km/h)
North Sea	15 - 30	39.1 - 64.8
Wadden Sea	10 - 20	29.8 - 54.1
Westerschelde	15 - 20	39.1 - 54.1

Table 1: Based on the equation $c = \sqrt{gh}$. Expected wave speeds in the three different regions based on their average water depths plus and minus the 1953 storm surge of 3m (Wolf & Flather, 2005).

However, given the existence of intertidal areas and intertidal mud flats in the Wadden Sea and Westerschelde respectively, local patterns in this might be different, as these areas play a vital role in controlling water depth.

2 Methods

The data analysis was conducted using Python version 3.11 ("Python", 2022). In the following subsections, the methodologies will be explained in more detail.

2.1 Datasets

Large scale trends can be observed if dataset is sufficiently large. Observed (measured) water level data (observed WL) was taken from the Gesla3 dataset (Woodworth et al., 2016; Haigh et al., 2021; "Gesla 3", 2021). The observed tidal data was compared with astronomic tide (astro WL), taken from Rijkswaterstaat (2025). Figure 14 shows from which locations astronomic and observed water levels were taken.

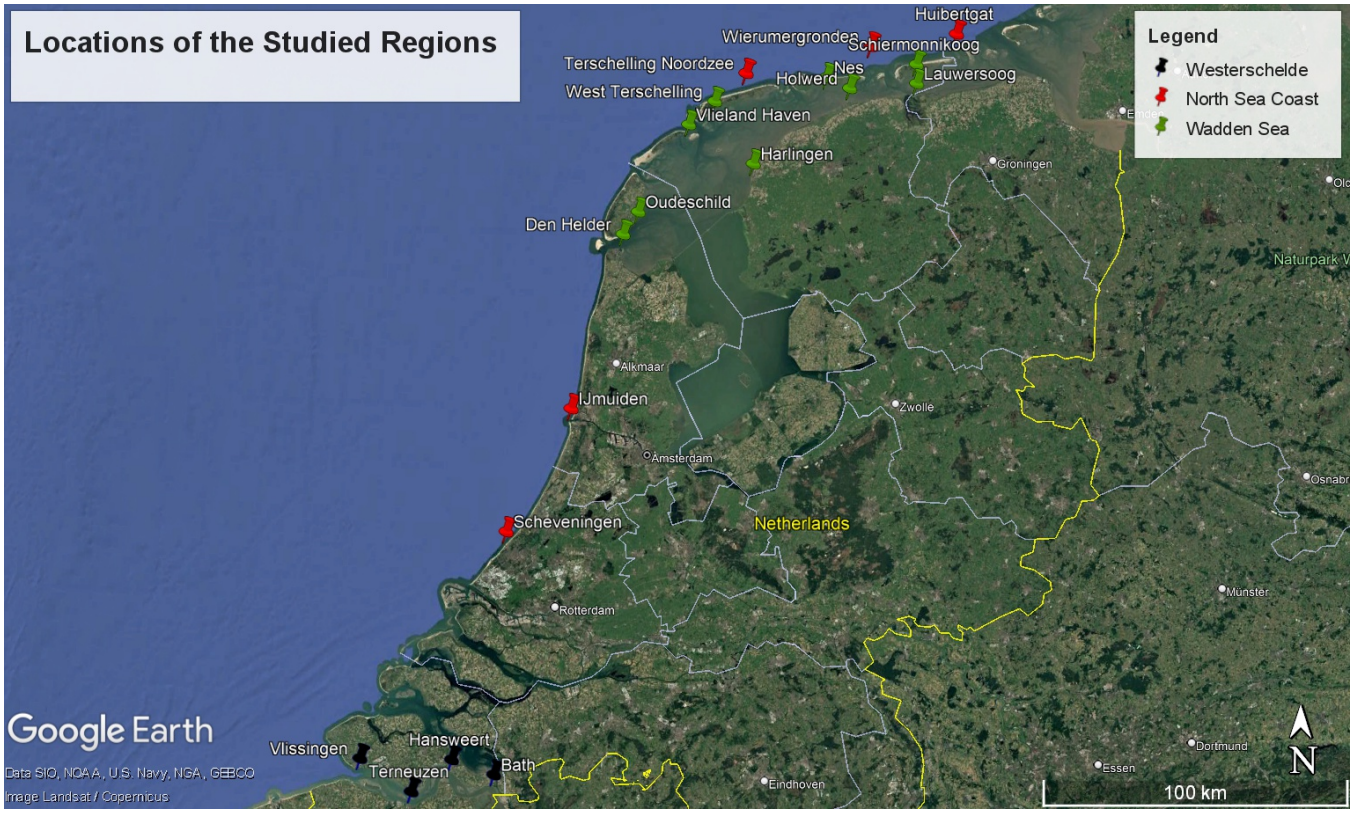


Figure 14: Locations where observed and astronomic water levels were used. Picture taken from "Google Earth Pro" (2025).

The earliest data in the Gesla3 dataset date back to 1960. For some locations the Gesla3 dataset stopped around 2015, therefore the data range to filter was set from 01-01-1960 to 01-01-2015. At some locations, the start date of the dataset was was later than 1960, either in the Gesla3 dataset or in the astronomic tide data from Rijkswaterstaat. For all locations, the astronomic tide resolution was 10 minutes. For the observed water levels, measurements where

taken every three hours from 1960-1971; every hour from 1971-1987; and every 10 minutes from 1987-2015. Table 2 was created to show for each location the minimum date range and the minimum number of datapoints (depending on the smallest dataset, either being the observed or the astronomic dataset).

Sub-Area (Region)	Location	Date Range	Number of Datapoints
North Sea	Scheveningen	01/01/1989 - 01/01/2015	1,340,219
	IJmuiden	01/01/1981 - 01/01/2015	1,830,319
	Terschelling Noordzee	01/01/1989 - 01/01/2015	1,359,072
	Wierumergronden	01/01/1987 - 01/01/2015	1,498,298
	Huibertgat	02/09/1987 - 01/01/2015	1,463,299
Westerschelde	Vlissingen	01/01/1960 - 01/01/2015	2,385,145
	Terneuzen	01/01/1988 - 01/01/2015	1,454,190
	Hansweert	01/01/1960 - 01/01/2015	1,388,930
	Bath	01/01/1988 - 01/01/2015	1,454,698
Wadden Sea	Den Helder	01/01/1960 - 01/01/2015	2,380,587
	Oudeschild	01/01/1990 - 01/01/2015	1,338,359
	Vlieland Haven	01/01/1990 - 01/01/2015	1,340,244
	Harlingen	01/01/1960 - 01/01/2015	1,645,238
	West Terschelling	01/01/1960 - 01/01/2015	1,591,423
	Nes	01/01/1990 - 01/01/2015	1,340,154
	Holwerd	01/01/1990 - 01/01/2015	824,642
	Schiermonnikoog	08/02/1989 - 01/01/2015	1,341,123
	Lauwersoog	01/01/1969 - 01/01/2015	1,583,879

Table 2: Dataset locations with date ranges.

2.2 Smoothing data and finding surges

The astronomic tide is not the only water level variations that ends up in the the gauge. On a short timescale, water levels are determined by tide, storm surges, waves and atmospheric pressure. Given this fact, it is important to make sure that during peak water levels, the data is smoothed. This was done by finding peaks and filtering peaks that fall within a 150 minute window and averaging the found heights. Then the average timestamp of the found peaks was taken for this newly calculated peak. Figure 15 shows an example of how this was done.

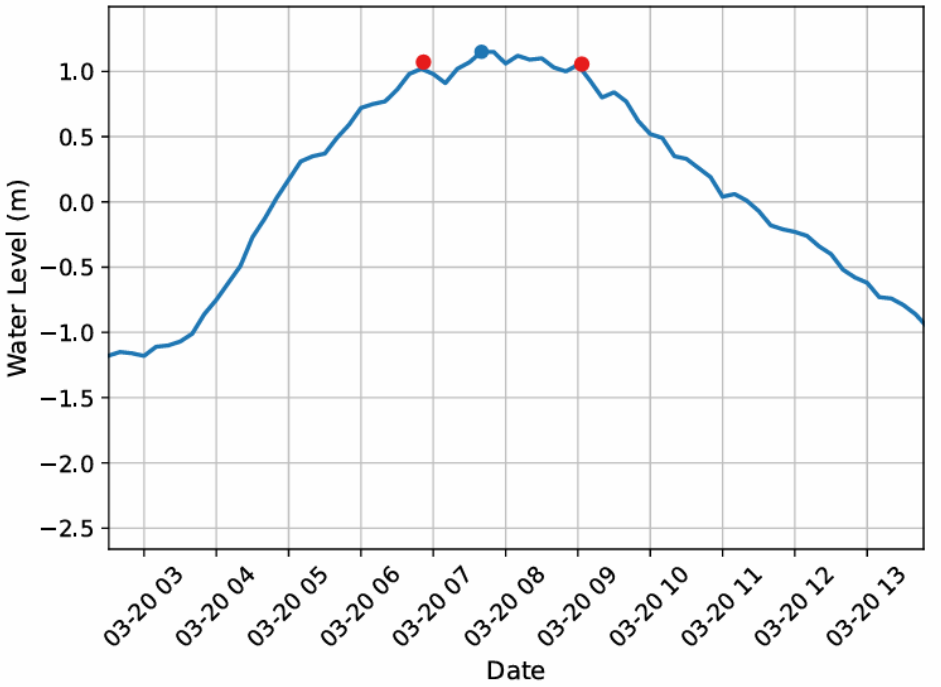


Figure 15: Schematic example of how peaks were filtered. In red the found peaks. Smoothing these 2 peaks gives a new peak in blue.

Given this study's focus on tide-surge interactions, it is important to know what the storm surge is at a given moment in order to say something meaningful about the surges' influence on tide. To find the storm surge, there are many filters to choose from, all with their own advantages and drawbacks. For this study, two methods to filter the storm surge were used: the skew surge and Godin filter.

The first is the skew surge (De Vries et al., 1995). The skew surge has been shown to be a very good method at quantifying the storm surge and is often much better at it than the residual (Sterl et al., 2009; Howard et al., 2010; Batstone et al., 2013; Mawdsley & Haigh, 2016). An example of the skew surge can be seen in figure 16. The skew surge is calculated by subtracting the highest observed WL and subtracting it with the highest astronomic WL per tidal cycle. This way, maximum surplus of water level is stored and shifts in the observed water level compared to the astronomic tide are ignored. The downside is that only single values can be stored per tidal cycle, and thus the continuous storm surge can be lost. However, skew surge is one of the best measures for maximum water levels analyses (Feng et al., 2021) and can therefore be used in cases where the results can be coupled to the skew surge.

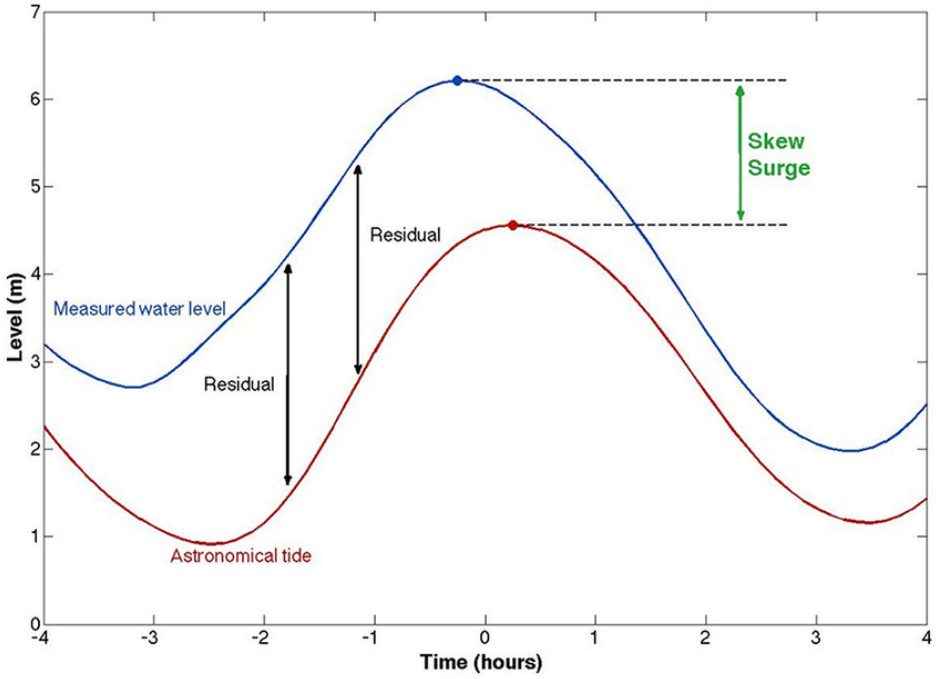


Figure 16: Example sketch of sew surge (green text). Figure source: Mawdsley and Haigh (2016).

From figure 16 in black we see the residual. The residual is the observed WL minus the astronomic WL at the same timestamp. Because of this, the residual shows both the storm surge component and the tide-surge interaction component. Given that this paper needed a clear storm surge component, the residual was not used for data analysis.

The other method to find surges was the Godin filter. This filter is relatively strong at filtering out smaller variations, coastal waves, from the observed water level signal (Walters & Heston, 1982). However, no filter is perfect, and as stated in Walters and Heston (1982), the Godin filter will start to show severe attenuation with wave periods around the 2-3 day mark. The largest storm surges period also lies around the 2-3 day period mark. From figure 8 we can conclude that the likeliest periods that are ignored by the Godin filter are the surges categorised as forerunners. Figure 17 shows an example of the Godin filtered WL from the observed WL.

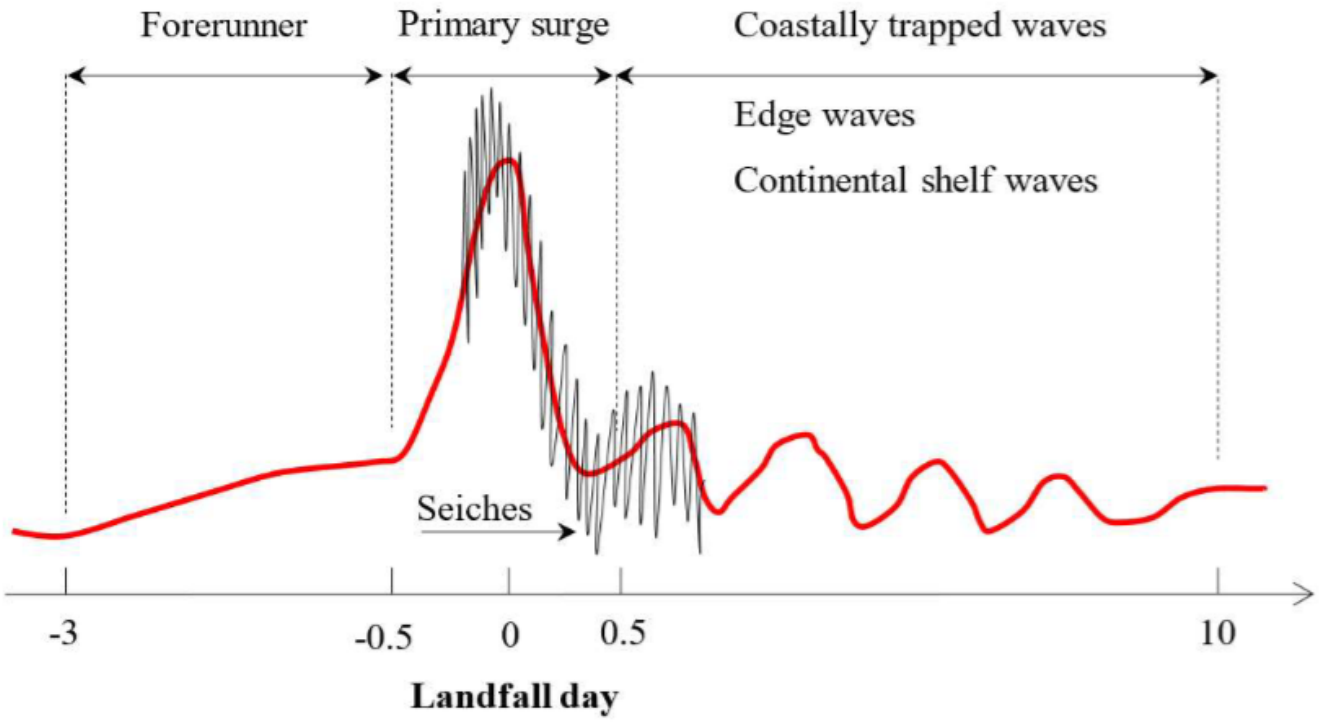


Figure 8 repeat: Categories of the storm surge. The red line is the example of the surge. Figure source: Bui (2021).

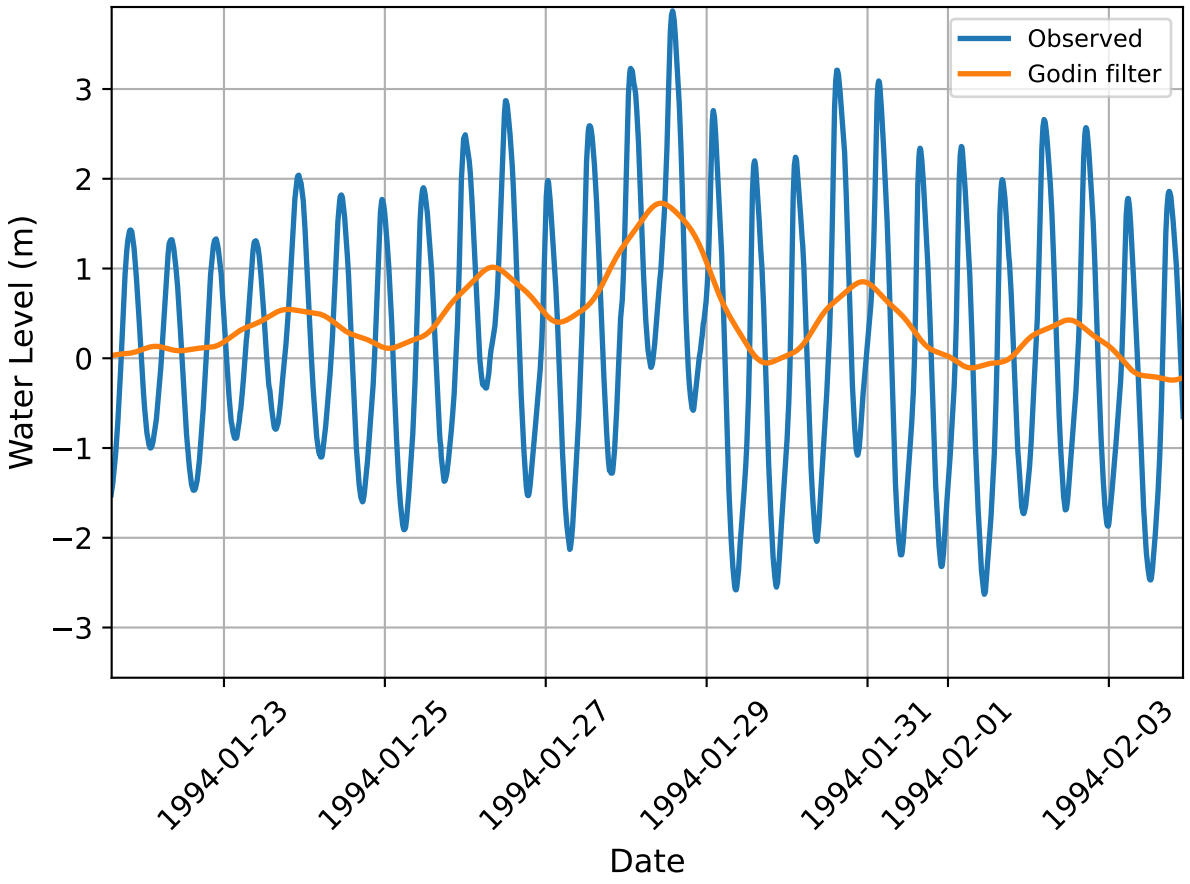


Figure 17: Example of the Godin filtered water level from the observed water level.

2.3 Calculations and results generation

For the changes in water level, the Godin filtered water level was plotted against the observed WL. The Godin filter was chosen for this case, to differentiate between higher water levels during not just the peak WL, thus there was a need for a continuous surge component. Then a t-test was performed on the slopes of the trend lines between the locations. This tests whether the difference between the slopes is significantly different from one another. If a slope differs significantly, this indicates that the surge has a stronger influence in one location or region than another. Also the confidence interval (the range of slopes that could theoretically be true based on the data) was calculated, to test whether the slopes are accurate.

For surge influence on the tidal range, the skew surge was used. This is because both the skew surge and the tidal range can be classified as single moments in the tidal cycle and can therefore be coupled. Equation 1 shows how to calculate the skew surge and equation 2 the tidal range. Furthermore, the tidal range was splitted for high high tide and low high tide, to further filter out some scatter.

$$\text{Skew Surge} = (H_{\text{obs, max}} - H_{\text{astr, max}})_{\text{per tidal cycle}} \tag{1}$$

Here the H stands for the water level. Obs and astr stand for observed and astronomic respectively.

$$\text{Tidal Range} = (H_{max} - H_{min})_{\text{per tidal cycle}} \tag{2}$$

Furthermore, since the tidal range might become larger due to the storm surge, we can also calculate the tidal range difference between the observed tidal range and the astronomic tidal range. This is an easy way to show at which surge height the tidal range has changed the most. Equation 3 shows how to calculate the tidal range difference.

$$\text{Tidal Range Difference} = (\text{Tidal Range})_{obs} - (\text{Tidal Range})_{astr} \tag{3}$$

To understand whether the timing of the tide shifts more during a storm, the observed WL were filtered for moments when the Godin filtered WL fell into a certain range. These ranges (or groups) being: -1.25 to -0.75; -0.75 to -0.25; -0.25 to 0.25; 0.25 to 0.75; 0.75 to 1.25; and >1.25. This way it is possible to test if larger surge heights cause earlier high or low tide. Within these groups, peak and minimum water levels were found. To find if the observed tide arrived earlier than astronomically predicted, equation 4 was used, for high tide and low tide. It was filtered to only find peaks within 6 hours, as then the next high water or low water of the tide arrives. Furthermore, if the tide would have shifted more than 6 hours, that would mean that the tide has run in anti-phase compared to the astronomic tide, which is very unlikely. Next, the two timestamps of the peaks were subtracted from each other. Note that the observed WL is subtracted from the astronomic WL. This means that if the astronomic WL is later than the observed WL, then the time difference will have a negative sign. Therefore, a negative time difference indicates that the observed WL occurred earlier than the astronomic WL. Here, t is the time stamp of a certain water level. T-tests between surges were also executed, to test if the means of the time difference between surge groups were significantly different from one another. In other words, this tested whether the surge height significantly influenced the timing of the high or low water. It is possible to compare any group with another, but in this study, the groups were tested consecutive from each other (so -1.25 to -0.75 with -0.75 to -0.25, then -0.75 to -0.25 with -0.25 and 0.25, etc.) and all surge groups were tested with the group with the most measurements (that being -0.25 to 0.25). The first method shows whether surges groups significantly shift the timing of high and low tide enough from each other, while the latter indicates if a certain surge group significantly altered the timing of high or low water compared to moments with little or no surge.

$$\text{Time Difference} = (t_{H_{\text{obs}}} - t_{H_{\text{astr}}})_{\text{within 6 hours}} \tag{4}$$

Also for the wave speed, the observed WL was filtered with the Godin filtered water levels, with the same ranges as for the time difference. This has the same reason as for the time differences, where differentiating between surge heights can show shifts in the wave speed distributions due to the surge. Similar to the time difference, the same t-tests were performed to test significant shifts. The wave speed is calculated using equation 5. Here v stands for the speed. The distance was measured using "Google Earth Pro" (2025). In order to calculate the wave speed, the correct peaks between locations need to be correlated. Therefore, while looking at the signals, it was hand determined that the peaks should fall within a certain time window, depending on the region. Where the two peaks fell within that time window, the wave speed was then calculated.

(5) $$v_{wave} = \frac{Distance_{\text{loc2, loc1}}}{t_{loc2} - t_{loc1}}$$

It is also possible to perform a cross-correlation. The way this works is by shifting one signal along the time axis and seeing where it fits another signal the best. The amount of shift necessary for the maximum fit is then the time difference. This can be performed for both the wave speed between locations and time difference within a location. Figure 18 shows an example of a shifted signal. Again the observed WL was filtered for certain Godin filter WL heights. Then, within a surge range, the observed WL was sliced into chunks of one tidal cycle. The astronomic WL dataset was also sliced into chunks of one tidal cycle. Then the cross-correlation between the observed WL and astronomic WL was performed.

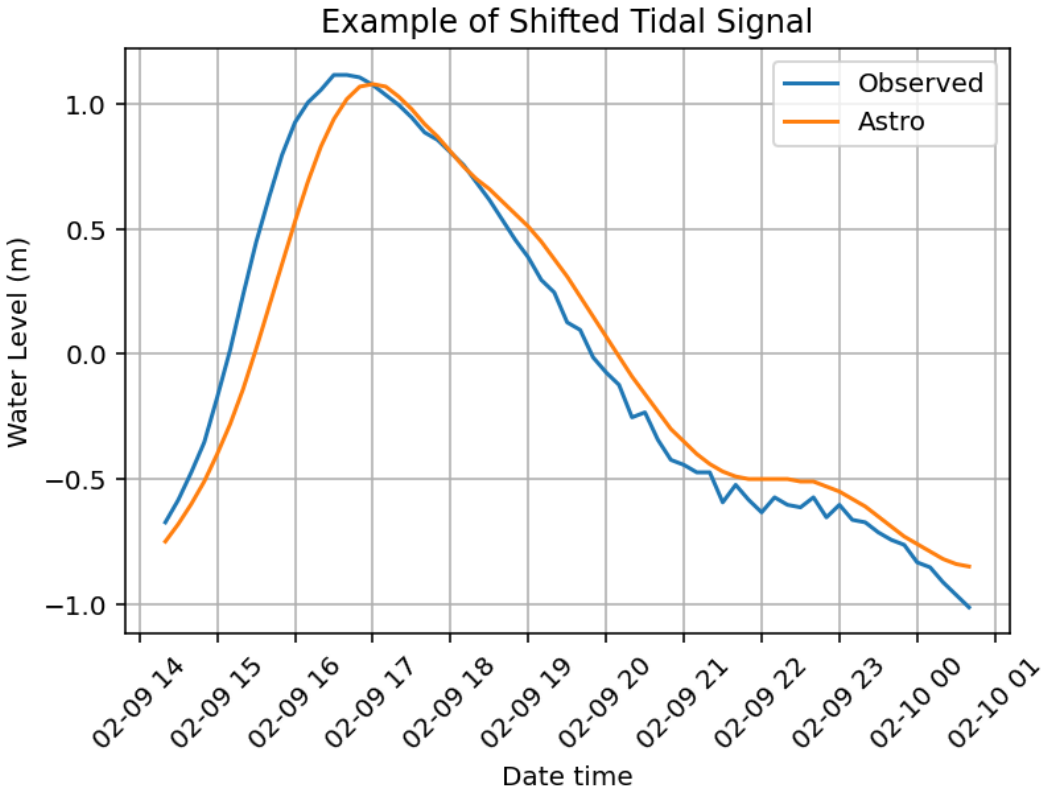


Figure 18: Example of a fully shifted tidal signal.

Symbol	Definition
H	Water level
t	Timestamp in yyyy/mm/dd
v	Speed

Table 3: Symbols for the equations and their definitions.

3 Results

3.1 Observed water levels.

Figure 19 shows the Godin filtered WL vs the observed WL during high tide and spring tide. We can see that R^2 is very high for all locations and that there is a very clear upward trend for the highest Godin filtered values when compared to the observed WL. Most trend lines lie close to each other, but in the Westerschelde, the trend lines are parallelly increasing the further inland (towards Bath) the wave goes. This is explained by the fact that the tidal range increases along the Westerschelde estuary (Wang et al., 2019), therefore, peak water levels increases along with them. These trendlines show how strong the surge has influenced the observed water level. If compared with other processes, a slope smaller than 1 means that the impact of the surge is less strong on the observed WL, while a slope larger than 1 means that a surge has a stronger impact on the observed WL.

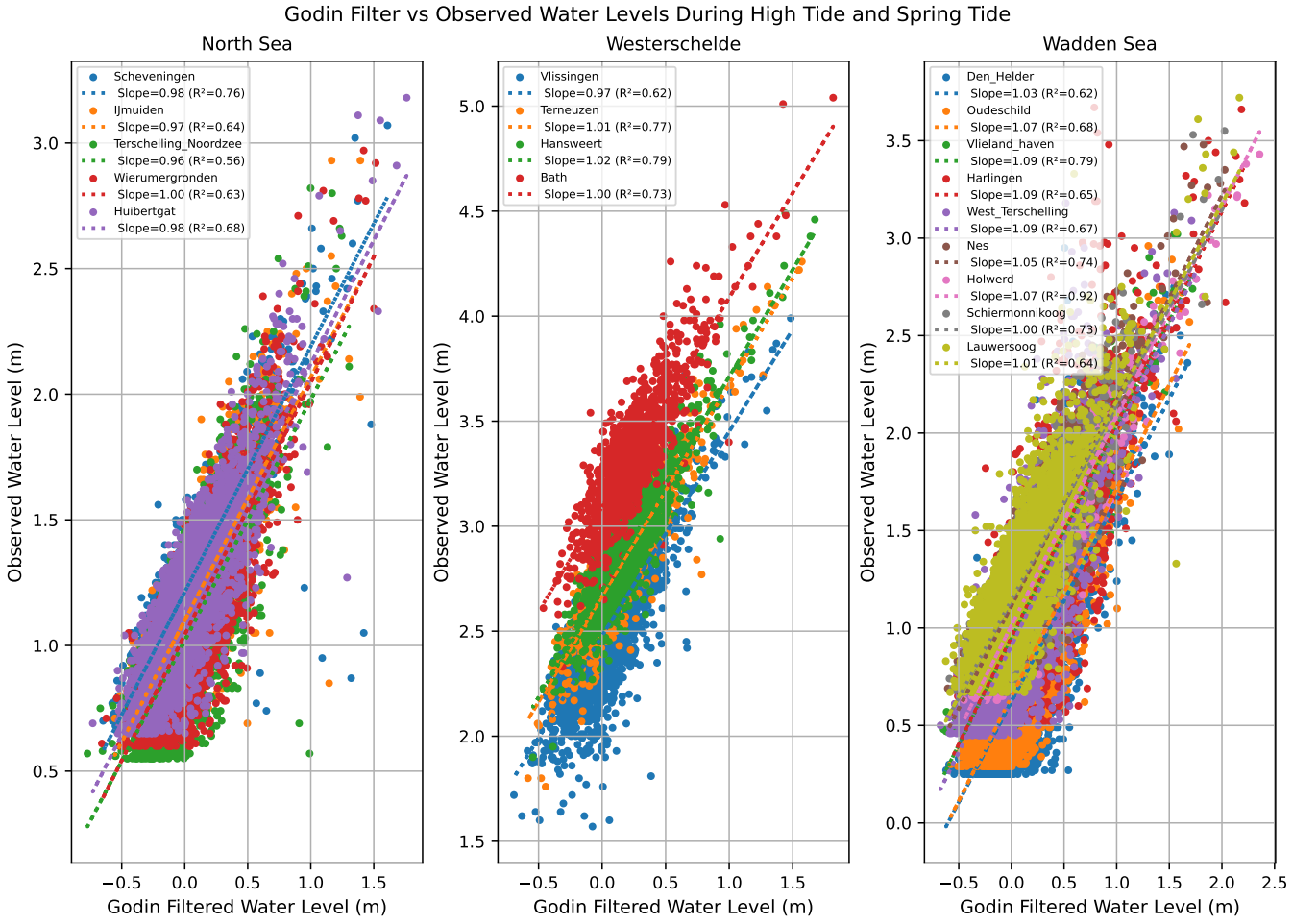


Figure 19: Godin filtered water levels vs observed WL.

The uncertainty of the slopes was tested by finding the confidence interval and checking if this did not fall too far from the slope plotted. As we can see from table 4, the plotted slopes fall within a maximum of 0.03 range from the confidence interval. This is very precise and thus a tight relationship between surge water levels and observed water levels can be claimed.

Region	Location	Slope	CI Lower	CI Upper
North Sea	Scheveningen	0.95	0.93	0.97
North Sea	IJmuiden	0.97	0.95	0.99
North Sea	Terschelling Noordzee	0.96	0.94	0.98
North Sea	Wierumergronden	1.00	0.98	1.02
North Sea	Huibertgat	0.99	0.97	1.00
Westerschelde	Vlissingen	0.97	0.95	0.99
Westerschelde	Terneuzen	1.01	0.99	1.03
Westerschelde	Hansweert	1.02	0.99	1.04
Westerschelde	Bath	1.00	0.97	1.03
Wadden Sea	Den Helder	1.03	1.02	1.04
Wadden Sea	Oudeschild	1.06	1.05	1.08
Wadden Sea	Vlieland haven	1.08	1.07	1.10
Wadden Sea	Harlingen	1.10	1.08	1.11
Wadden Sea	West Terschelling	1.09	1.08	1.11
Wadden Sea	Nes	1.05	1.03	1.07
Wadden Sea	Holwerd	1.07	1.06	1.09
Wadden Sea	Schiermonnikoog	1.00	0.98	1.02
Wadden Sea	Lauwersoog	1.00	0.99	1.02

Table 4: Slope confidence. CI stands for the confidence interval, thus the CI lower and CI upper together indicate the range the slope could be true.

Additionally, a t-test was conducted to compare slopes of different locations within a region, to asses whether the slope differences were statistically significant. The null-hypothesis tested was that since the slopes all lie within 0.1 form each other, there is no significant difference in the slopes' values. A p-value below 0.05 was taken to be significantly low for the null-hypothesis to be rejected. In other words, if the p-value was below 0.05, the trend line slopes are significantly different from each other. Table 5 shows which locations within a region had a significant, or very close to significant, slope from another location.

Region	Location1	Location2	P-value	Significant
North Sea	IJmuiden	Wierumergronden	0.0240	True
North Sea	Terschelling Noordzee	Wierumergronden	0.0042	True
North Sea	Terschelling Noordzee	Huibertgat	0.0819	False
Westerschelde	Vlissingen	Terneuzen	0.0271	True
Westerschelde	Vlissingen	Hansweert	0.0055	True
Wadden Sea	Oudeschild	Vlieland haven	0.0954	False
Wadden Sea	Oudeschild	Harlingen	0.0250	True
Wadden Sea	Oudeschild	West Terschelling	0.0193	True
Wadden Sea	Oudeschild	Schiermonnikoog	0.0000	True
Wadden Sea	Oudeschild	Lauwersoog	0.0000	True
Wadden Sea	Vlieland haven	Nes	0.0051	True
Wadden Sea	Vlieland haven	Schiermonnikoog	0.0000	True
Wadden Sea	Vlieland haven	Lauwersoog	0.0000	True
Wadden Sea	Harlingen	Nes	0.0009	True
Wadden Sea	Harlingen	Holwerd	0.0650	False
Wadden Sea	Harlingen	Schiermonnikoog	0.0000	True
Wadden Sea	Harlingen	Lauwersoog	0.0000	True
Wadden Sea	West Terschelling	Nes	0.0006	True
Wadden Sea	West Terschelling	Holwerd	0.0516	False
Wadden Sea	West Terschelling	Schiermonnikoog	0.0000	True
Wadden Sea	West Terschelling	Lauwersoog	0.0000	True
Wadden Sea	Nes	Holwerd	0.0712	False
Wadden Sea	Nes	Schiermonnikoog	0.0001	True
Wadden Sea	Nes	Lauwersoog	0.0015	True
Wadden Sea	Holwerd	Schiermonnikoog	0.0000	True
Wadden Sea	Holwerd	Lauwersoog	0.0000	True

Table 5: T-test significance test. P-values below 0.05 are seen as a significant difference between slopes. Only significantly low p-values are shown, or the ones that are very close to 0.05.

Interestingly, significant slope difference are not often observed along the North Sea coastline. It is mostly when the tide and surge interact in the Westerschelde and Wadden Sea that we see that the slopes are significantly different. Within the Wadden Sea one pattern that emerges is that the stations near the inlets have a significantly different slope from each other. Another pattern in the Wadden Sea is that within a tidal basin, the slopes of the mainland locations compared to the inlet locations are almost significant. Furthermore, the slope differences are also often (nearly) significant between mainland locations. This means that the surge has a significantly different influence on the observed WL between the back barrier basins.

Two key observations emerge. Firstly, surges tend to be of a stronger influence on the observed water level in the Westerschelde and Wadden Sea compared to the North Sea. Secondly, within the regions a slope difference larger than 0.03 is enough of a difference to be significant. Even a slope difference of 0.02 is very close to being significantly different.

Since we see a trend in higher observed water levels for larger surges, it is was expected that storm surges also influence tidal ranges. Given that the tidal range is a single moment within the tidal cycle, we can compare tidal range with the skew surge (see figure 20). We observe an upward trend for some locations, most notably in the Westerschelde, and for Scheveningen and IJmuiden in the North Sea. The R^2 is still much lower than compared with the trendline fits of figure 19. In the Wadden Sea there is no trend to speak of. All locations show a poor fit and scatter is very large. Given this, it is not possible to speak of a surge correlation with the tidal range in the Wadden Sea. Only for the Westerschelde, there is a consistent influence of the surge on the tidal range, though the fit is small.

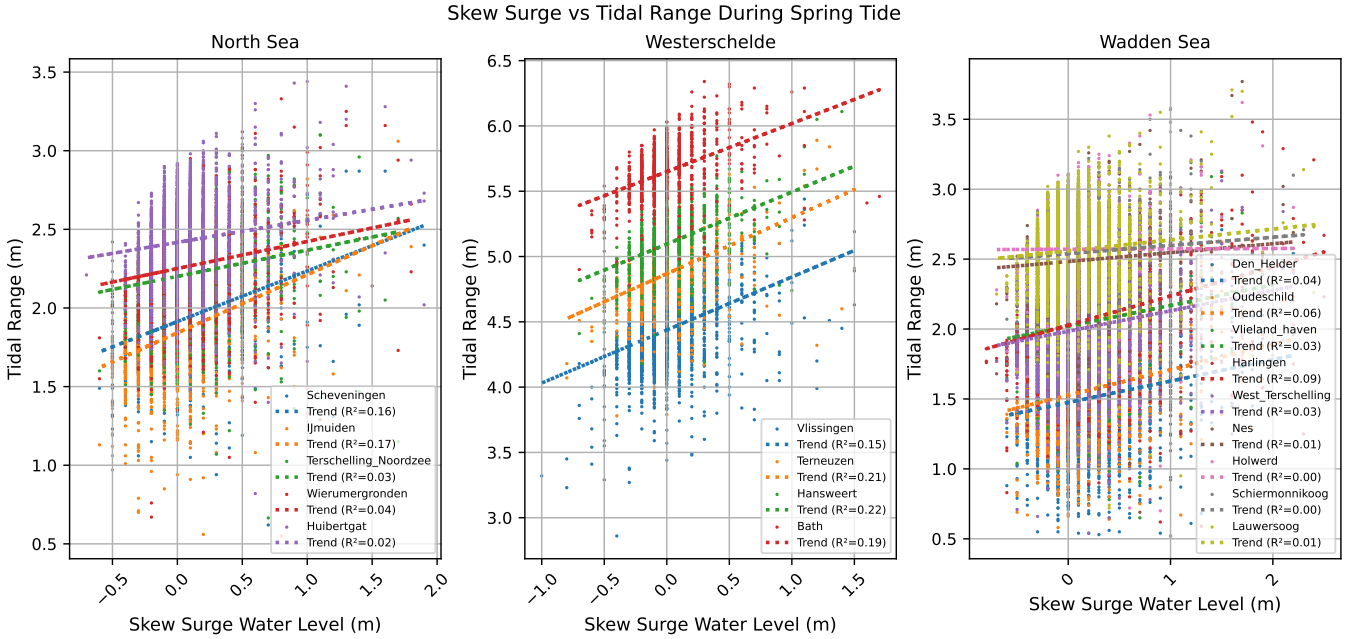


Figure 20: Skew Surge Water Level vs Tidal Range.

To check in another way if storm has an impact on the tidal range, the tidal range difference between the observed tidal range and astronomic tidal range was plotted. Figure 21 shows the skew surge vs the tidal range difference (see equation 3). The trendlines here indicates if a surge has a larger effect on the difference between the observed tidal range and the astronomic tidal range. However, the spread is again very large, and most R^2 values are low. However, only a few locations have a R^2 value close to 0.2, these locations being: Scheveningen, IJmuiden, Hansweert, Oudeschild and Harlingen. The Westerchelde is the only region where the trendlines of each location consistently increase, all in the same direction. This is again, the only region where we can speak of a small correlation between larger surges and increases in tidal range. Within the North Sea we only see an increase for the Southern most locations, being Scheveningen and IJmuiden, and can only speak of a small correlation for those two locations.

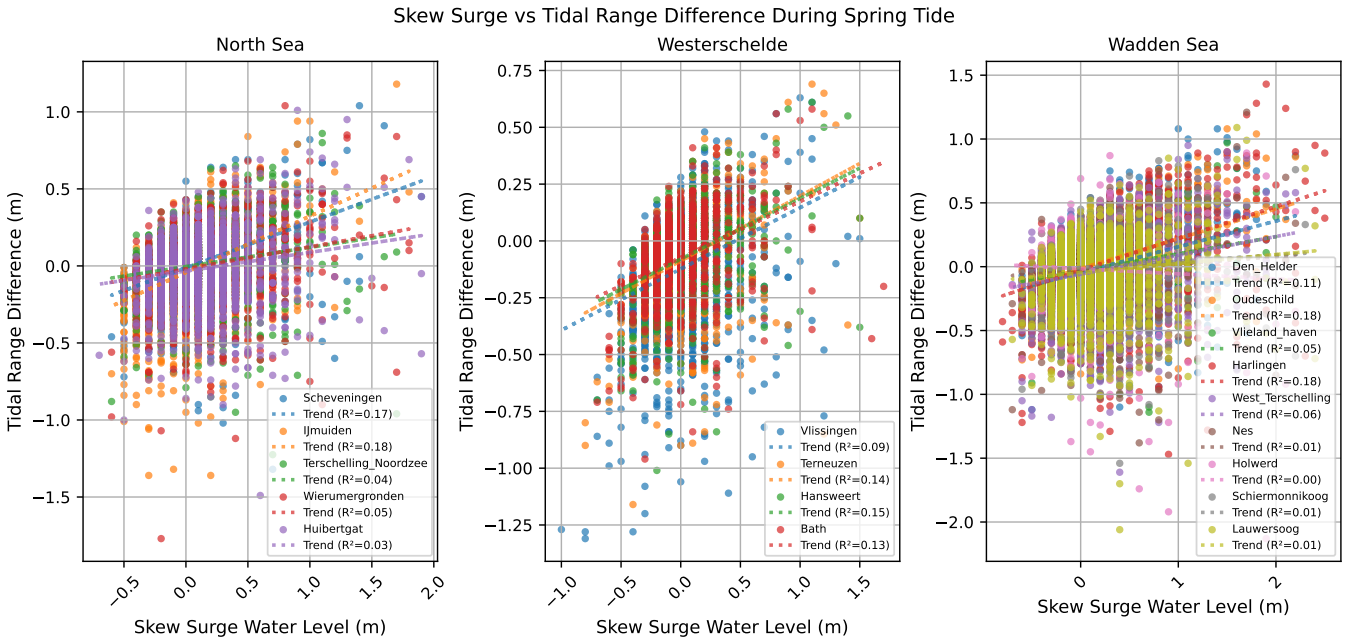


Figure 21: Skew Surge vs the Tidal range difference.

When checking for high high tide and low high tide tidal range, it resulted in very similar plots and results as shown in figures 20 and 21. Therefore, also differentiating between high high tide and low high tide does not change the storm impact on the tidal range.

3.2 Timing of the tide.

First, the results of the timing of the full tidal cycle are shown, obtained by cross-correlations. Figure 22 shows the time difference distribution of the full tidal cycle for different surge heights. The reason only the North Sea is shown, is because the plot is almost the same for the Westerschelde and Wadden Sea. Furthermore, the t-test performed on the time difference distribution for the full tidal cycle yielded that no significant change is present. With this in mind, and the result shown in figure 22, we can say that there is no significant change in timing for the full tidal cycle.

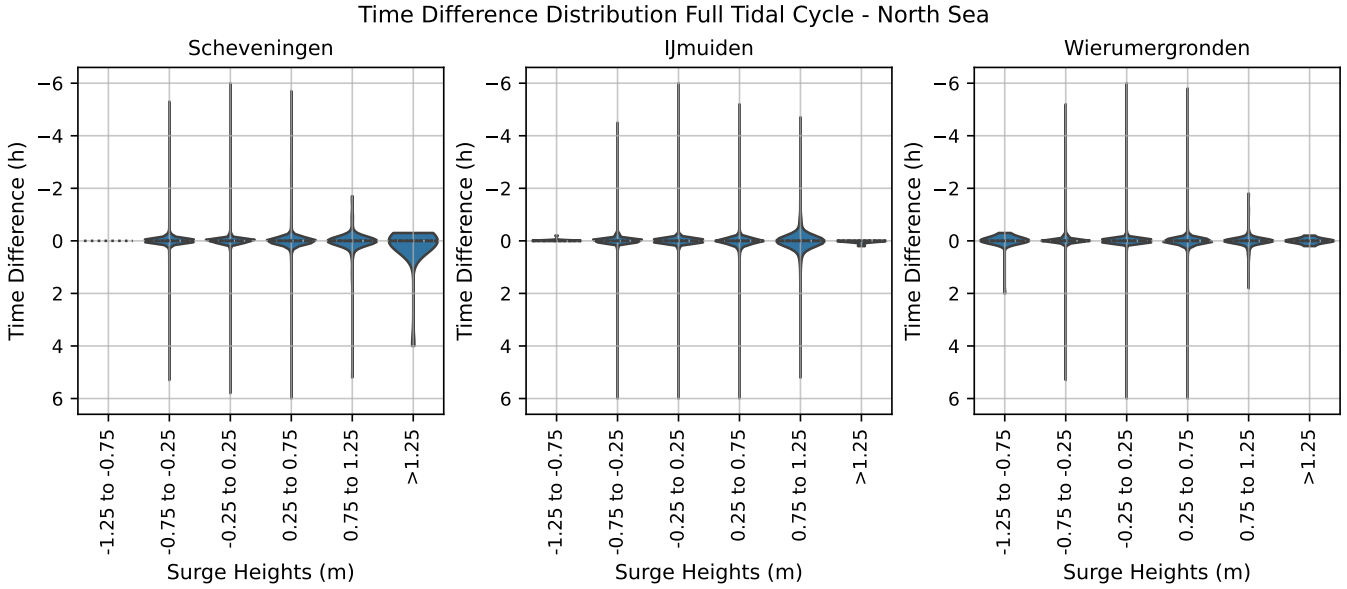


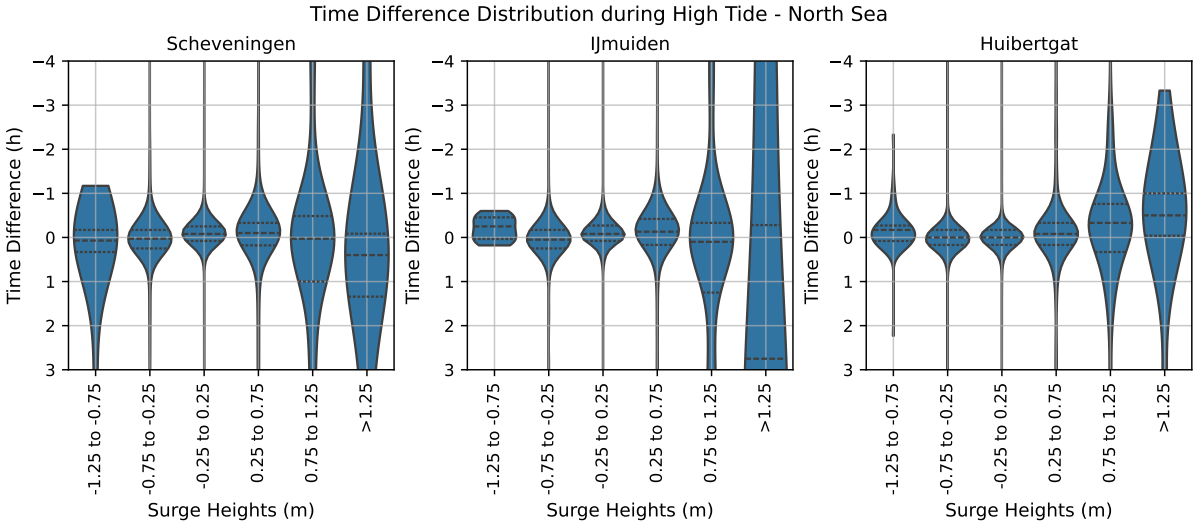
Figure 22: Time difference distribution of the full tidal cycle for different surge heights. Negative time differences indicate an earlier observed WL compared to the astronomic WL.

Furthermore, the timing difference of high and low tide of the observed WL compared to the astronomic WL was. The results will be presented through violin plots, as this effectively shows the distribution of the time differences. Additionally, violin plots function as boxplots, where we can see the first and third quartile and the median. Not all locations are plotted, as most plots looked similar within each of the regions. Therefore, the plots shown are of locations that show a similar pattern as other locations in the region. Note that here we only look at the distribution of time differences, not the absolute number of times a certain time difference occurred. This was done so that the quartiles and median distribution is easier to see, and shifts in the time difference distribution is clear. Also note that the y-axis is inverted, therefore the minus sign indicates that the observed high WL has arrived earlier than the astronomic high WL. The x-axis (surge heights) shows the Godin WL for which the observed WL was filtered.

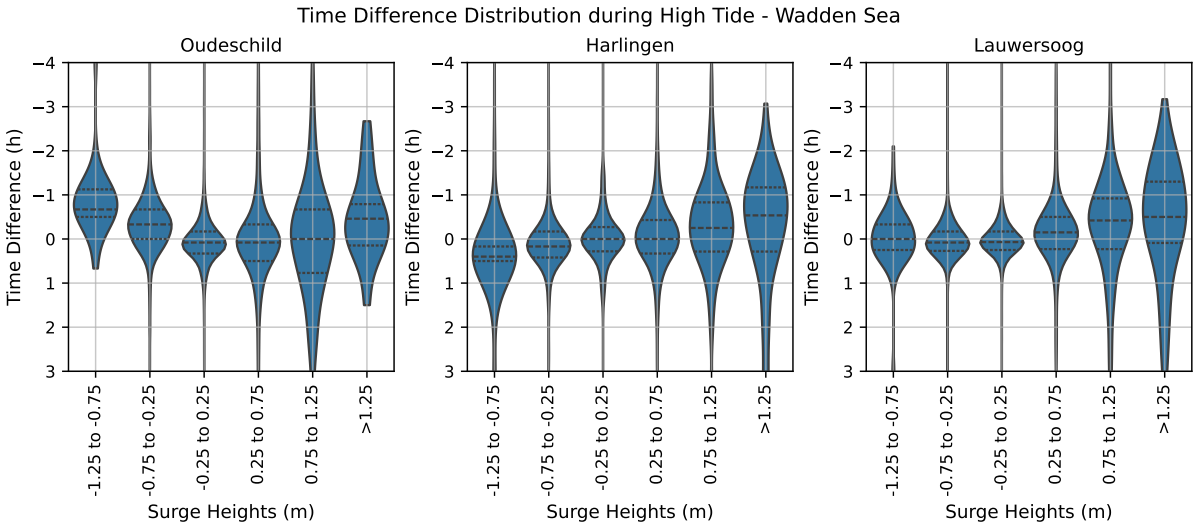
Figure 23 shows the distribution of time differences during high tide. Within the North Sea (figure 23a), for Scheveningen, the distribution does not shift much. The same can be said for IJmuiden. Huibertgat shows a small upward shift of the distribution, indicating that higher surges lead to earlier arrival of high tide. Given the small shifts in Scheveningen IJmuiden, we will take a look if the shifts for consecutive surge heights are significant. Table 6 shows that for the largest surge heights the changes in time differences are not significant, when compared with the previous group. However, when comparing with the -0.25 to 0.25 group (table 7), the shifts in time difference at larger surge heights are significant. We can therefore say that the timing of the high tide in Scheveningen and IJmuiden is affected by the surge height, but larger storms do not alter the timing significantly further. For Huibertgat the t-tests in table 6 show that up to the last two surge groups, the shifts in time difference are significant. When comparing with the -0.25 to 0.25 group (table 7) we see a significant shift for all groups, except for the smallest and largest surges. This indicates that surge does create significant shifts in the timing of high tide for Huibertgat, however, these changes are not significant for extreme surges. The p-values are, however, very close to 0.05 for the highest and lowest surge groups. We can therefore say, that except for the most extreme surges, there is a correlation where larger surge heights cause earlier observed high tide.

Within the Wadden Sea (see figure 23b) we see earlier high tide (negative time difference) with larger surges. In Oudeschild there is also a negative shift when surges become smaller. Given table 7 we see that these shifts are significant when compared with the -0.25 to 0.25 group, apart from comparison with the 0.75 to 1.25 group. For Harlingen and Lauwersoog we can see an upward trend of the time differences, indicating earlier high tides due to surge heights. The t-tests in table 6 supports this, apart from the smallest and largest surge groups. However, table 7 shows that for Harlingen these time differences are significantly different when compared with the -0.25 to 0.25 group. Given this we can say that there is a correlation between larger surge heights and a earlier observed high tide. On closer inspection all the locations near the tidal inlet in the Wadden Sea show a similar pattern as Oudeschild, and locations at the mainland show similar patterns as Harlingen and Lauwersoog.

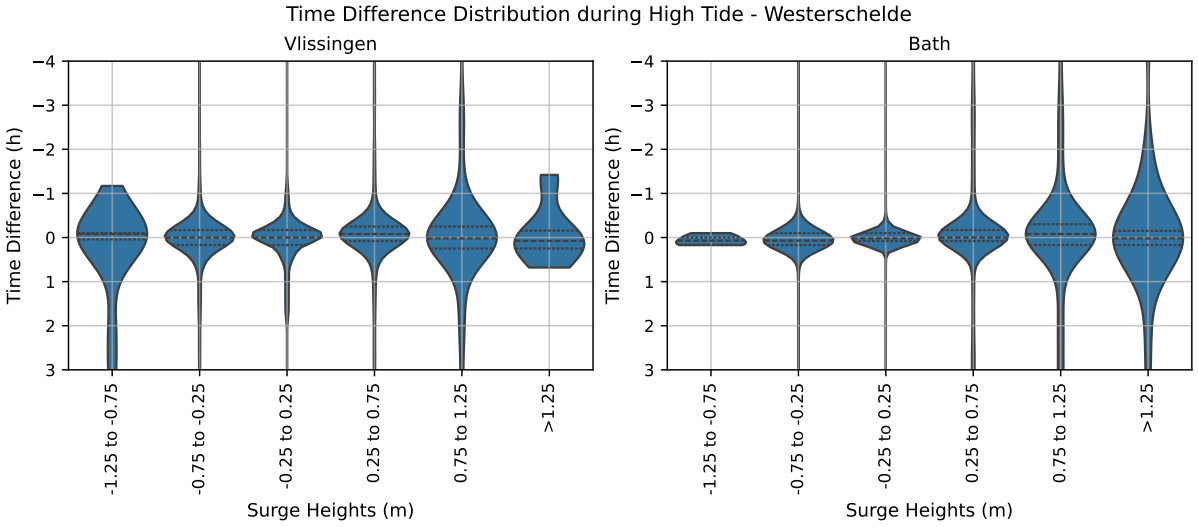
In the Westerschelde we can see that the time difference shifts very little, if at all (figure 23c). Table 6 and table 7 reflect this, only the -0.75 to -0.25 and 0.25 to 0.75 groups compared with the -0.25 to 0.25 group show significant change. There is, then, no correlation between surge height and time difference of the observed water level during high tide in the Westerschelde.



(a) North Sea



(b) Wadden Sea



(c) Westerschelde

Figure 23: Time difference occurrences for the three studied regions during high tide. The dashed lines in each plot are the first and third quartile and the median. Negative time differences indicate an earlier observed high tide than astronomic high tide.

Region	Location	Storm1	Storm2	P-Value	Significant
Westerschelde	Bath	-1.25 to -0.75	-0.75 to -0.25	0.972	False
Westerschelde	Bath	-0.75 to -0.25	-0.25 to 0.25	0.014	True
Westerschelde	Bath	-0.25 to 0.25	0.25 to 0.75	0.011	True
Westerschelde	Bath	0.25 to 0.75	0.75 to 1.25	0.420	False
Westerschelde	Bath	0.75 to 1.25	>1.25	0.625	False
Wadden Sea	Harlingen	-1.25 to -0.75	-0.75 to -0.25	0.390	False
Wadden Sea	Harlingen	-0.75 to -0.25	-0.25 to 0.25	0.000	True
Wadden Sea	Harlingen	-0.25 to 0.25	0.25 to 0.75	0.031	True
Wadden Sea	Harlingen	0.25 to 0.75	0.75 to 1.25	0.000	True
Wadden Sea	Harlingen	0.75 to 1.25	>1.25	0.865	False
North Sea	Huibertgat	-1.25 to -0.75	-0.75 to -0.25	0.005	True
North Sea	Huibertgat	-0.75 to -0.25	-0.25 to 0.25	0.000	True
North Sea	Huibertgat	-0.25 to 0.25	0.25 to 0.75	0.000	True
North Sea	Huibertgat	0.25 to 0.75	0.75 to 1.25	0.078	False
North Sea	Huibertgat	0.75 to 1.25	>1.25	0.937	False
North Sea	IJmuiden	-1.25 to -0.75	-0.75 to -0.25	0.116	False
North Sea	IJmuiden	-0.75 to -0.25	-0.25 to 0.25	0.000	True
North Sea	IJmuiden	-0.25 to 0.25	0.25 to 0.75	0.000	True
North Sea	IJmuiden	0.25 to 0.75	0.75 to 1.25	0.006	True
North Sea	IJmuiden	0.75 to 1.25	>1.25	0.240	False
Wadden Sea	Lauwersoog	-1.25 to -0.75	-0.75 to -0.25	0.399	False
Wadden Sea	Lauwersoog	-0.75 to -0.25	-0.25 to 0.25	0.001	True
Wadden Sea	Lauwersoog	-0.25 to 0.25	0.25 to 0.75	0.000	True
Wadden Sea	Lauwersoog	0.25 to 0.75	0.75 to 1.25	0.006	True
Wadden Sea	Lauwersoog	0.75 to 1.25	>1.25	0.765	False
Wadden Sea	Oudeschild	-1.25 to -0.75	-0.75 to -0.25	0.000	True
Wadden Sea	Oudeschild	-0.75 to -0.25	-0.25 to 0.25	0.000	True
Wadden Sea	Oudeschild	-0.25 to 0.25	0.25 to 0.75	0.006	True
Wadden Sea	Oudeschild	0.25 to 0.75	0.75 to 1.25	0.707	False
Wadden Sea	Oudeschild	0.75 to 1.25	>1.25	0.080	False
North Sea	Scheveningen	-1.25 to -0.75	-0.75 to -0.25	0.089	False
North Sea	Scheveningen	-0.75 to -0.25	-0.25 to 0.25	0.000	True
North Sea	Scheveningen	-0.25 to 0.25	0.25 to 0.75	0.000	True
North Sea	Scheveningen	0.25 to 0.75	0.75 to 1.25	0.630	False
North Sea	Scheveningen	0.75 to 1.25	>1.25	0.336	False
Westerschelde	Vlissingen	-1.25 to -0.75	-0.75 to -0.25	0.601	False
Westerschelde	Vlissingen	-0.75 to -0.25	-0.25 to 0.25	0.012	True
Westerschelde	Vlissingen	-0.25 to 0.25	0.25 to 0.75	0.000	True
Westerschelde	Vlissingen	0.25 to 0.75	0.75 to 1.25	0.811	False
Westerschelde	Vlissingen	0.75 to 1.25	>1.25	0.820	False

Table 6: T-test between surges of the time difference during high tide. Here each surge range is compared with the previous surge range. A p-value smaller than 0.05 indicates that the means between the two storms are significantly different from one another.

Region	Location	Storm1	Storm2	P-Value	Significant
Westerschelde	Bath	-0.25 to 0.25	-1.25 to -0.75	0.830	False
Westerschelde	Bath	-0.25 to 0.25	-0.75 to -0.25	0.014	True
Westerschelde	Bath	-0.25 to 0.25	0.25 to 0.75	0.011	True
Westerschelde	Bath	-0.25 to 0.25	0.75 to 1.25	0.339	False
Westerschelde	Bath	-0.25 to 0.25	>1.25	0.121	False
Wadden Sea	Harlingen	-0.25 to 0.25	-1.25 to -0.75	0.001	True
Wadden Sea	Harlingen	-0.25 to 0.25	-0.75 to -0.25	0.000	True
Wadden Sea	Harlingen	-0.25 to 0.25	0.25 to 0.75	0.031	True
Wadden Sea	Harlingen	-0.25 to 0.25	0.75 to 1.25	0.000	True
Wadden Sea	Harlingen	-0.25 to 0.25	>1.25	0.000	True
North Sea	Huibertgat	-0.25 to 0.25	-1.25 to -0.75	0.069	False
North Sea	Huibertgat	-0.25 to 0.25	-0.75 to -0.25	0.000	True
North Sea	Huibertgat	-0.25 to 0.25	0.25 to 0.75	0.000	True
North Sea	Huibertgat	-0.25 to 0.25	0.75 to 1.25	0.000	True
North Sea	Huibertgat	-0.25 to 0.25	>1.25	0.079	False
North Sea	IJmuiden	-0.25 to 0.25	-1.25 to -0.75	0.333	False
North Sea	IJmuiden	-0.25 to 0.25	-0.75 to -0.25	0.000	True
North Sea	IJmuiden	-0.25 to 0.25	0.25 to 0.75	0.000	True
North Sea	IJmuiden	-0.25 to 0.25	0.75 to 1.25	0.000	True
North Sea	IJmuiden	-0.25 to 0.25	>1.25	0.000	True
Wadden Sea	Lauwersoog	-0.25 to 0.25	-1.25 to -0.75	0.678	False
Wadden Sea	Lauwersoog	-0.25 to 0.25	-0.75 to -0.25	0.001	True
Wadden Sea	Lauwersoog	-0.25 to 0.25	0.25 to 0.75	0.000	True
Wadden Sea	Lauwersoog	-0.25 to 0.25	0.75 to 1.25	0.000	True
Wadden Sea	Lauwersoog	-0.25 to 0.25	>1.25	0.000	True
Wadden Sea	Oudeschild	-0.25 to 0.25	-1.25 to -0.75	0.000	True
Wadden Sea	Oudeschild	-0.25 to 0.25	-0.75 to -0.25	0.000	True
Wadden Sea	Oudeschild	-0.25 to 0.25	0.25 to 0.75	0.006	True
Wadden Sea	Oudeschild	-0.25 to 0.25	0.75 to 1.25	0.716	False
Wadden Sea	Oudeschild	-0.25 to 0.25	>1.25	0.000	True
North Sea	Scheveningen	-0.25 to 0.25	-1.25 to -0.75	0.017	True
North Sea	Scheveningen	-0.25 to 0.25	-0.75 to -0.25	0.000	True
North Sea	Scheveningen	-0.25 to 0.25	0.25 to 0.75	0.000	True
North Sea	Scheveningen	-0.25 to 0.25	0.75 to 1.25	0.002	True
North Sea	Scheveningen	-0.25 to 0.25	>1.25	0.002	True
Westerschelde	Vlissingen	-0.25 to 0.25	-1.25 to -0.75	0.340	False
Westerschelde	Vlissingen	-0.25 to 0.25	-0.75 to -0.25	0.012	True
Westerschelde	Vlissingen	-0.25 to 0.25	0.25 to 0.75	0.000	True
Westerschelde	Vlissingen	-0.25 to 0.25	0.75 to 1.25	0.447	False
Westerschelde	Vlissingen	-0.25 to 0.25	>1.25	0.477	False

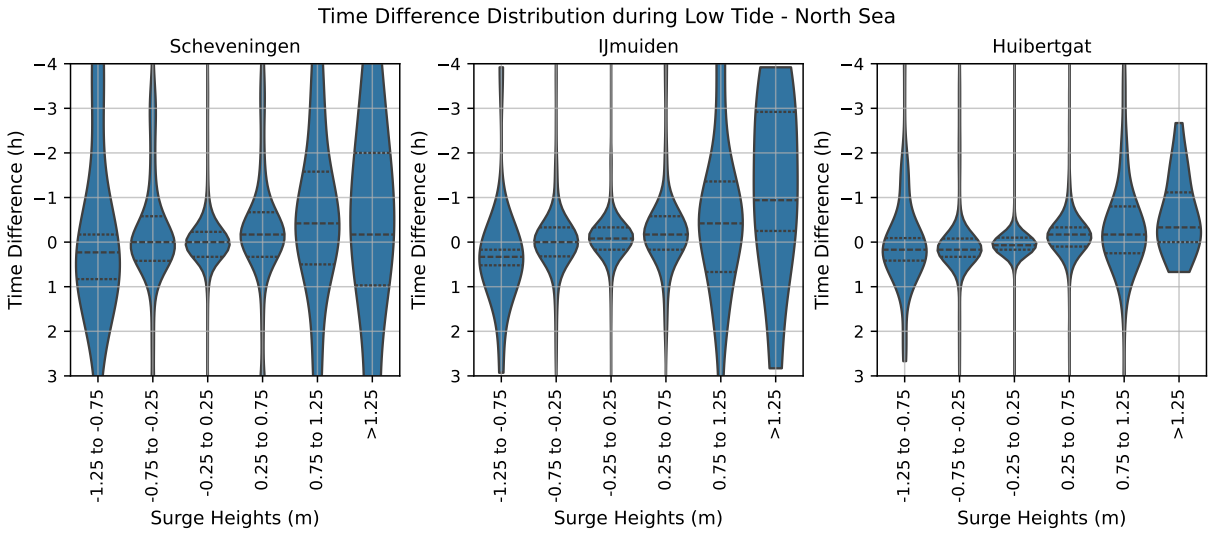
Table 7: T-test between surges of the time difference during high tide. Here, all surge ranges per location were compared with the -0.25 to 0.25 surge range. A p-value smaller than 0.05 indicates that the means of the time differences between the two surge range are significantly different from one another.

Figure 24 shows the time difference distributions during low tide, with the surge height groups on the x-axis and the time difference on the y-axis. Note that a negative time difference means that the low observed low tide arrived earlier than the astronomic low tide. Again, only the locations shown are similar to other locations in the regions.

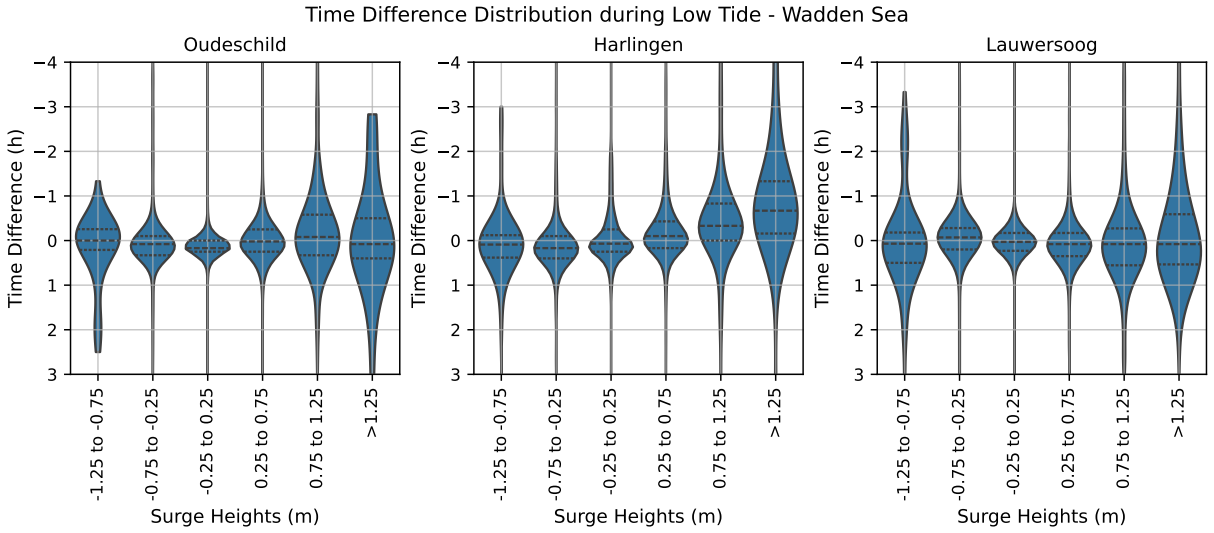
During low tide, we can see that for the North Sea (see figure 24a) higher surges, correlate to earlier low tides (more negative time difference). When looking at the t-test results from table 8, we can see that the difference between consecutive surge groups are often not significant, however when looking at table 9 we see that the differences are almost always significantly different from the -0.25 to 0.25 group. Therefore, the surge height correlate with earlier low tides in the North Sea, however, the changes from one surge group to another are minimal.

In the Wadden Sea (figure 24b) we can see for Oudeschild that the changes are very minimal, but significant between storms, except for the most extreme surges (table 8). However, when comparing with the -0.25 to 0.25 group we do see that there is a significant shift between the surges, except for the most negative surges 9. Looking very closely, these shifts are similar to the ones seen in during high tide for Oudeschild (figure 23b). Therefore, surges do affect timing of low water in Ouderschild, but less severely. In Harlingen, there is again a clear upward trend of earlier low tide with higher surges. Table 8 shows that the most extreme surges are not significantly shifted compared with the less extreme surges. However, when comparing with only the -0.25 to 0.25 group (table 9) we do see that for all surges, these shifts are significant. Therefore in Harlingen, larger surges show a correlation with earlier observed low tide. In Lauwersoog we do not see much shift during low tide. The trend even seems to go downward, in other words, the observed low tide appears to arrive later than the astronomic low tide. However, when looking at the significance, tables 8 and 9 show that only for small surges the shifts are significant. Therefore, at Lauwersoog, there is no correlation for surge height on the timing of low tide.

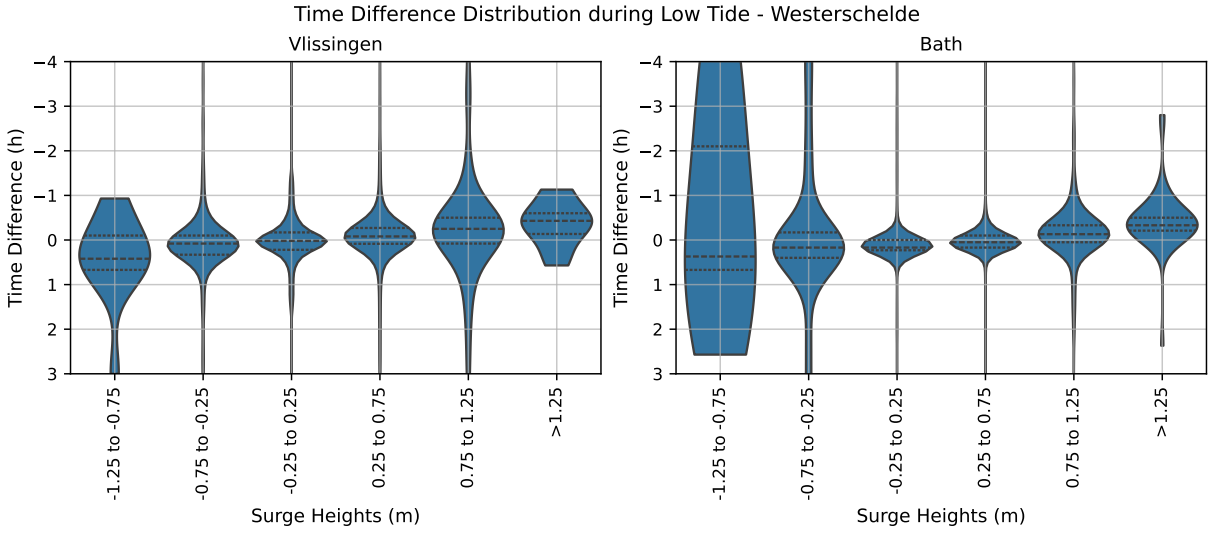
For the Westerschelde (figure 24c), we can see for both locations that larger surges correlate with earlier low tide (negative time difference). When looking at consecutive surges, in Vlissingen, only the shifts from the negative surge groups are significant (table 8). However, when comparing with the -0.25 to 0.25 group (table 9) we see that the surge groups are significantly different from the little to no surge group. In Bath, only the most negative surge group is not significant when compared with the next surge group (table 8). The same thing can be said when all groups are compared with the -0.25 to 0.25 group (table 9). There is therefore a correlation between larger surge heights and earlier observed low tide.



(a) North Sea



(b) Wadden Sea



(c) Westerschelde

Figure 24: Time difference occurrences for the three studied regions during low tide. A negative time difference means that the observed WL has arrived earlier than the astronomic WL. The dashed lines in each plot are the first and third quartile and the median.

Region	Location	Storm1	Storm2	P-Value	Significant
Westerschelde	Bath	-1.25 to -0.75	-0.75 to -0.25	0.530	False
Westerschelde	Bath	-0.75 to -0.25	-0.25 to 0.25	0.002	True
Westerschelde	Bath	-0.25 to 0.25	0.25 to 0.75	0.000	True
Westerschelde	Bath	0.25 to 0.75	0.75 to 1.25	0.000	True
Westerschelde	Bath	0.75 to 1.25	>1.25	0.032	True
Wadden Sea	Harlingen	-1.25 to -0.75	-0.75 to -0.25	0.826	False
Wadden Sea	Harlingen	-0.75 to -0.25	-0.25 to 0.25	0.000	True
Wadden Sea	Harlingen	-0.25 to 0.25	0.25 to 0.75	0.000	True
Wadden Sea	Harlingen	0.25 to 0.75	0.75 to 1.25	0.000	True
Wadden Sea	Harlingen	0.75 to 1.25	>1.25	0.108	False
North Sea	Huibertgat	-1.25 to -0.75	-0.75 to -0.25	0.778	False
North Sea	Huibertgat	-0.75 to -0.25	-0.25 to 0.25	0.062	False
North Sea	Huibertgat	-0.25 to 0.25	0.25 to 0.75	0.000	True
North Sea	Huibertgat	0.25 to 0.75	0.75 to 1.25	0.001	True
North Sea	Huibertgat	0.75 to 1.25	>1.25	0.379	False
North Sea	IJmuiden	-1.25 to -0.75	-0.75 to -0.25	0.259	False
North Sea	IJmuiden	-0.75 to -0.25	-0.25 to 0.25	0.223	False
North Sea	IJmuiden	-0.25 to 0.25	0.25 to 0.75	0.000	True
North Sea	IJmuiden	0.25 to 0.75	0.75 to 1.25	0.567	False
North Sea	IJmuiden	0.75 to 1.25	>1.25	0.286	False
Wadden Sea	Lauwersoog	-1.25 to -0.75	-0.75 to -0.25	0.396	False
Wadden Sea	Lauwersoog	-0.75 to -0.25	-0.25 to 0.25	0.000	True
Wadden Sea	Lauwersoog	-0.25 to 0.25	0.25 to 0.75	0.000	True
Wadden Sea	Lauwersoog	0.25 to 0.75	0.75 to 1.25	0.366	False
Wadden Sea	Lauwersoog	0.75 to 1.25	>1.25	0.472	False
Wadden Sea	Oudeschild	-1.25 to -0.75	-0.75 to -0.25	0.207	False
Wadden Sea	Oudeschild	-0.75 to -0.25	-0.25 to 0.25	0.000	True
Wadden Sea	Oudeschild	-0.25 to 0.25	0.25 to 0.75	0.000	True
Wadden Sea	Oudeschild	0.25 to 0.75	0.75 to 1.25	0.015	True
Wadden Sea	Oudeschild	0.75 to 1.25	>1.25	0.804	False
North Sea	Scheveningen	-1.25 to -0.75	-0.75 to -0.25	0.686	False
North Sea	Scheveningen	-0.75 to -0.25	-0.25 to 0.25	0.000	True
North Sea	Scheveningen	-0.25 to 0.25	0.25 to 0.75	0.000	True
North Sea	Scheveningen	0.25 to 0.75	0.75 to 1.25	0.039	True
North Sea	Scheveningen	0.75 to 1.25	>1.25	0.468	False
Westerschelde	Vlissingen	-1.25 to -0.75	-0.75 to -0.25	0.423	False
Westerschelde	Vlissingen	-0.75 to -0.25	-0.25 to 0.25	0.000	True
Westerschelde	Vlissingen	-0.25 to 0.25	0.25 to 0.75	0.000	True
Westerschelde	Vlissingen	0.25 to 0.75	0.75 to 1.25	0.055	False
Westerschelde	Vlissingen	0.75 to 1.25	>1.25	0.711	False

Table 8: T-test between surges of the time difference during low tide. Here each surge range is compared with the previous surge range. A p-value smaller than 0.05 indicates that the means of the time differences between two surges are significantly different from one another.

Region	Location	Storm1	Storm2	P-Value	Significant
Westerschelde	Bath	-0.25 to 0.25	-1.25 to -0.75	0.105	False
Westerschelde	Bath	-0.25 to 0.25	-0.75 to -0.25	0.002	True
Westerschelde	Bath	-0.25 to 0.25	0.25 to 0.75	0.000	True
Westerschelde	Bath	-0.25 to 0.25	0.75 to 1.25	0.000	True
Westerschelde	Bath	-0.25 to 0.25	>1.25	0.000	True
Wadden Sea	Harlingen	-0.25 to 0.25	-1.25 to -0.75	0.042	True
Wadden Sea	Harlingen	-0.25 to 0.25	-0.75 to -0.25	0.000	True
Wadden Sea	Harlingen	-0.25 to 0.25	0.25 to 0.75	0.000	True
Wadden Sea	Harlingen	-0.25 to 0.25	0.75 to 1.25	0.000	True
Wadden Sea	Harlingen	-0.25 to 0.25	>1.25	0.000	True
North Sea	Huibertgat	-0.25 to 0.25	-1.25 to -0.75	0.292	False
North Sea	Huibertgat	-0.25 to 0.25	-0.75 to -0.25	0.062	False
North Sea	Huibertgat	-0.25 to 0.25	0.25 to 0.75	0.000	True
North Sea	Huibertgat	-0.25 to 0.25	0.75 to 1.25	0.000	True
North Sea	Huibertgat	-0.25 to 0.25	>1.25	0.000	True
North Sea	IJmuiden	-0.25 to 0.25	-1.25 to -0.75	0.080	False
North Sea	IJmuiden	-0.25 to 0.25	-0.75 to -0.25	0.223	False
North Sea	IJmuiden	-0.25 to 0.25	0.25 to 0.75	0.000	True
North Sea	IJmuiden	-0.25 to 0.25	0.75 to 1.25	0.000	True
North Sea	IJmuiden	-0.25 to 0.25	>1.25	0.000	True
Wadden Sea	Lauwersoog	-0.25 to 0.25	-1.25 to -0.75	0.457	False
Wadden Sea	Lauwersoog	-0.25 to 0.25	-0.75 to -0.25	0.000	True
Wadden Sea	Lauwersoog	-0.25 to 0.25	0.25 to 0.75	0.000	True
Wadden Sea	Lauwersoog	-0.25 to 0.25	0.75 to 1.25	0.880	False
Wadden Sea	Lauwersoog	-0.25 to 0.25	>1.25	0.144	False
Wadden Sea	Oudeschild	-0.25 to 0.25	-1.25 to -0.75	0.241	False
Wadden Sea	Oudeschild	-0.25 to 0.25	-0.75 to -0.25	0.000	True
Wadden Sea	Oudeschild	-0.25 to 0.25	0.25 to 0.75	0.000	True
Wadden Sea	Oudeschild	-0.25 to 0.25	0.75 to 1.25	0.000	True
Wadden Sea	Oudeschild	-0.25 to 0.25	>1.25	0.047	True
North Sea	Scheveningen	-0.25 to 0.25	-1.25 to -0.75	0.116	False
North Sea	Scheveningen	-0.25 to 0.25	-0.75 to -0.25	0.000	True
North Sea	Scheveningen	-0.25 to 0.25	0.25 to 0.75	0.000	True
North Sea	Scheveningen	-0.25 to 0.25	0.75 to 1.25	0.000	True
North Sea	Scheveningen	-0.25 to 0.25	>1.25	0.367	False
Westerschelde	Vlissingen	-0.25 to 0.25	-1.25 to -0.75	0.093	False
Westerschelde	Vlissingen	-0.25 to 0.25	-0.75 to -0.25	0.000	True
Westerschelde	Vlissingen	-0.25 to 0.25	0.25 to 0.75	0.000	True
Westerschelde	Vlissingen	-0.25 to 0.25	0.75 to 1.25	0.000	True
Westerschelde	Vlissingen	-0.25 to 0.25	>1.25	0.048	True

Table 9: T-test between surges of the time difference during low tide. Here, all surge ranges per location were compared with the -0.25 to 0.25 surge range. A p-value smaller than 0.05 indicates that the means of the time differences between the two surge ranges are significantly different from one another.

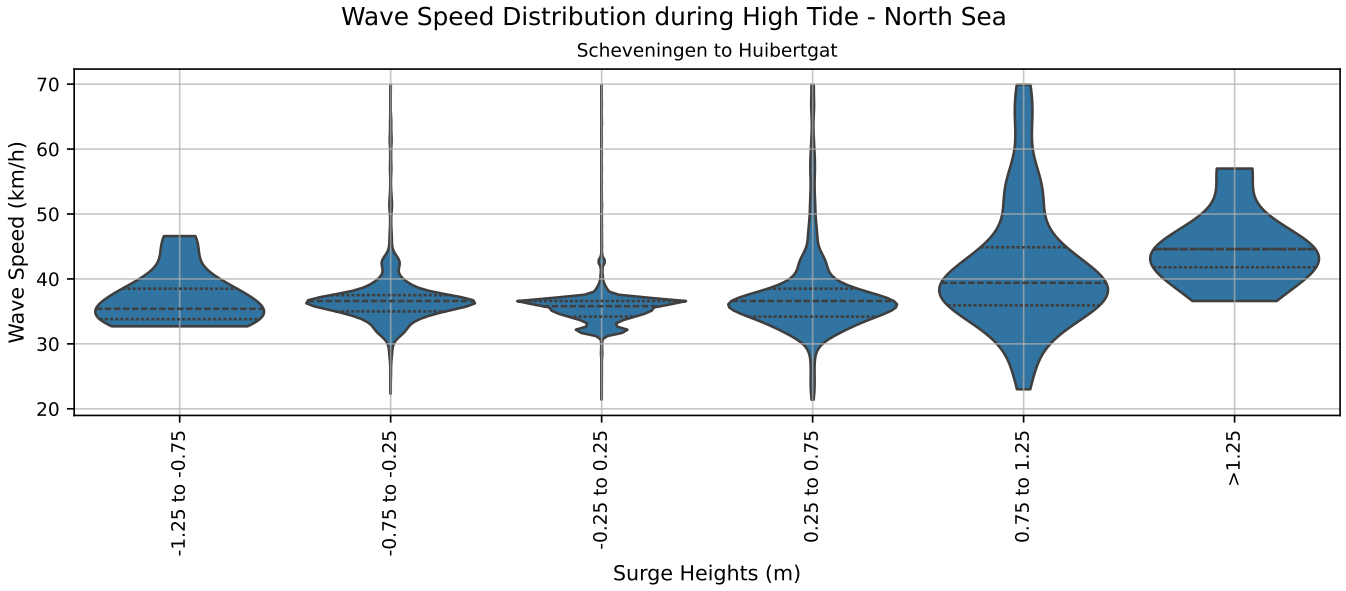
3.3 Tidal wave speed.

For the same reason as the time differences, the tidal wave speeds were plotted as violin plots. It is important to pay close attention to the quartiles and median here, as these sometimes might be so closely spaced together, that they appear to be one line. Note that the relative distribution of the wave speeds is plotted, not the total number of times a certain wave speed occurred.

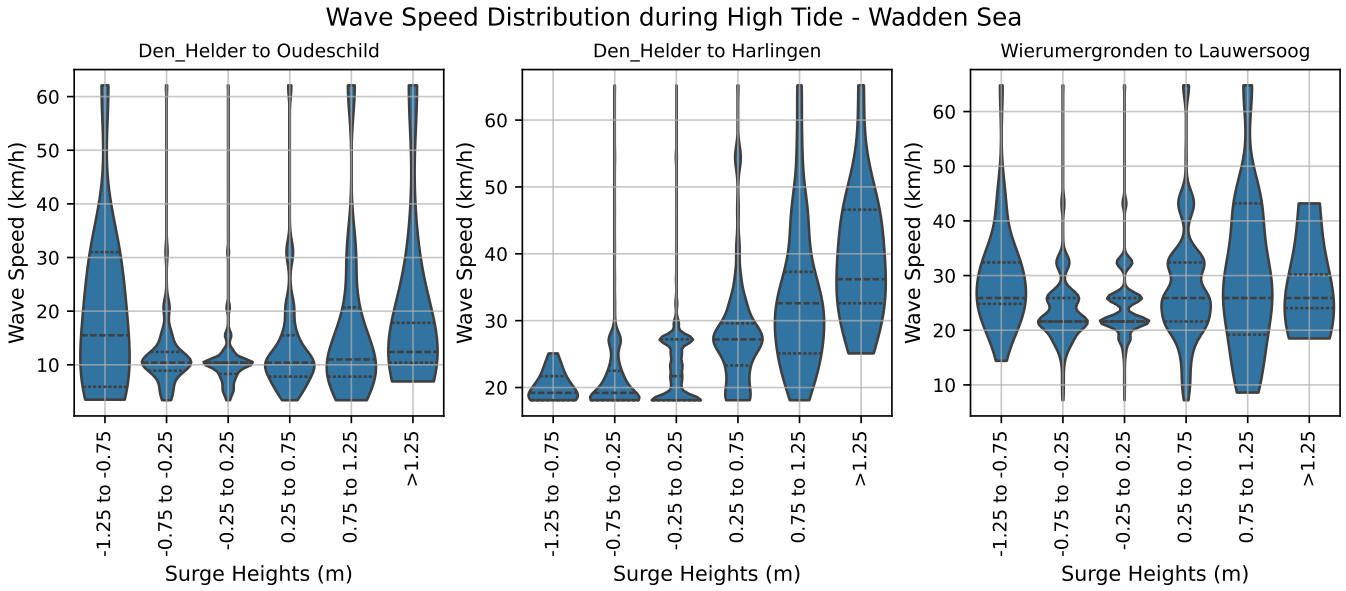
In figure 25 the wave speed distributions can be seen during high tide. In the North Sea during high tide (figure 25a) we see a clear shift in larger wave speeds with increasing surges. The differences between each consecutive surge group are significant, except for the most positive or negative surges (table 10). Comparing the surge groups with the -0.25 to 0.25 group, we do see that the wave speed shifts significantly, except for the most negative surge group (table 11). Therefore, there is a correlation with increasing surges and faster tidal waves during high tide in the North Sea.

In the Wadden Sea (figure 25b) we see that the wave speed from Den Helder to Oudeschild increases with larger surges. We also see an increase in wave speed with the most negative surges. These changes are significant for every consecutive surge group (table 10). Also when comparing each surge group with the -0.25 to 0.25 group do we see significant changes in wave speed (table 11). Wave speeds also increase with larger surge heights from Den Helder to Harlingen. Also here, the shifts in wave speeds are significant, both when looking at consecutive surge groups as well as comparing all surge groups with the -0.25 to 0.25 group (tables 10 and 11). From Wierumergronden to Lauwersoog we see a decrease in wave speed from negative surge to surges closer to zero, but not much change when looking at larger surges. When looking at the significance, we see that up the last two surge groups, the shifts are significant (table 10). When comparing with the -0.25 to 0.25 group, we see that only the shift of the >1.25 surge group is not significant. Given all this, we do see a correlation with wave speeds increasing when surges get larger up to a certain point.

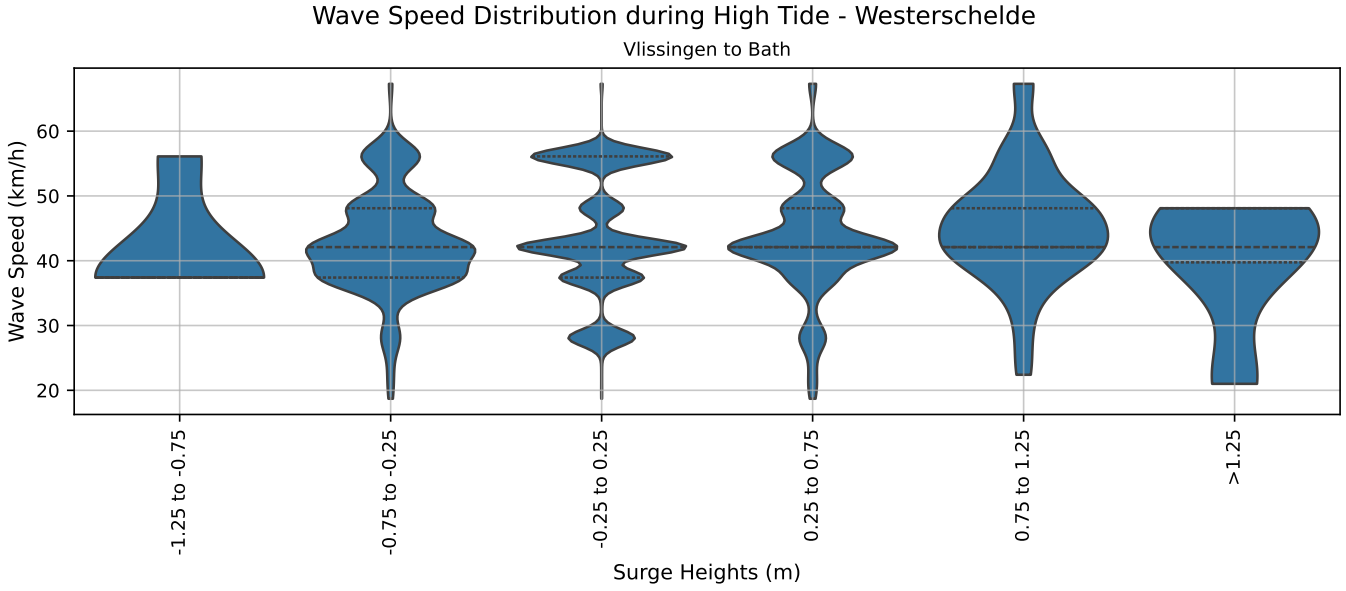
In the Westerschelde (figure 25c), we see very little shift in wave speeds when looking at the different surge heights. Also when performing the t-tests (tables 10 and 11) we see that there is only one group that has shifted significantly from the others, that being the -0.75 to -0.25 group compared with the -0.25 to 0.25 group. We see that this group has a slightly slower distribution of wave speeds. Given that the lowest surge group is cut off, there exists the possibility that wave speeds would have decreased further, but that is now unknown. In any case, wave speeds do not correlate with larger surges in the Westerschelde.



(a) North Sea



(b) Wadden Sea



(c) Westerschelde

Figure 25: Wave speed distributions for the three studied regions during high tide.

Region	Distance key	Storm1	Storm2	P-Value	Significant
Wadden Sea	Den Helder to Harlingen	-1.25 to -0.75	-0.75 to -0.25	0.376	False
Wadden Sea	Den Helder to Harlingen	-0.75 to -0.25	-0.25 to 0.25	0.000	True
Wadden Sea	Den Helder to Harlingen	-0.25 to 0.25	0.25 to 0.75	0.000	True
Wadden Sea	Den Helder to Harlingen	0.25 to 0.75	0.75 to 1.25	0.000	True
Wadden Sea	Den Helder to Harlingen	0.75 to 1.25	>1.25	0.017	True
Wadden Sea	Den Helder to Oudeschild	-1.25 to -0.75	-0.75 to -0.25	0.000	True
Wadden Sea	Den Helder to Oudeschild	-0.75 to -0.25	-0.25 to 0.25	0.000	True
Wadden Sea	Den Helder to Oudeschild	-0.25 to 0.25	0.25 to 0.75	0.000	True
Wadden Sea	Den Helder to Oudeschild	0.25 to 0.75	0.75 to 1.25	0.000	True
Wadden Sea	Den Helder to Oudeschild	0.75 to 1.25	>1.25	0.352	False
North Sea	Scheveningen to Huibertgat	-1.25 to -0.75	-0.75 to -0.25	0.895	False
North Sea	Scheveningen to Huibertgat	-0.75 to -0.25	-0.25 to 0.25	0.000	True
North Sea	Scheveningen to Huibertgat	-0.25 to 0.25	0.25 to 0.75	0.000	True
North Sea	Scheveningen to Huibertgat	0.25 to 0.75	0.75 to 1.25	0.000	True
North Sea	Scheveningen to Huibertgat	0.75 to 1.25	>1.25	0.480	False
Westerschelde	Vlissingen to Bath	-1.25 to -0.75	-0.75 to -0.25	0.646	False
Westerschelde	Vlissingen to Bath	-0.75 to -0.25	-0.25 to 0.25	0.006	True
Westerschelde	Vlissingen to Bath	-0.25 to 0.25	0.25 to 0.75	0.429	False
Westerschelde	Vlissingen to Bath	0.25 to 0.75	0.75 to 1.25	0.171	False
Westerschelde	Vlissingen to Bath	0.75 to 1.25	>1.25	0.078	False
Wadden Sea	Wierumergronden to Lauwersoog	-1.25 to -0.75	-0.75 to -0.25	0.000	True
Wadden Sea	Wierumergronden to Lauwersoog	-0.75 to -0.25	-0.25 to 0.25	0.000	True
Wadden Sea	Wierumergronden to Lauwersoog	-0.25 to 0.25	0.25 to 0.75	0.000	True
Wadden Sea	Wierumergronden to Lauwersoog	0.25 to 0.75	0.75 to 1.25	0.128	False
Wadden Sea	Wierumergronden to Lauwersoog	0.75 to 1.25	>1.25	0.842	False

Table 10: T-test between surges of the wave speeds during high tide. Here, each surge group is compared with the previous surge group. A p-value smaller than 0.05 indicates that the means of the time differences between two surges are significantly different from one another.

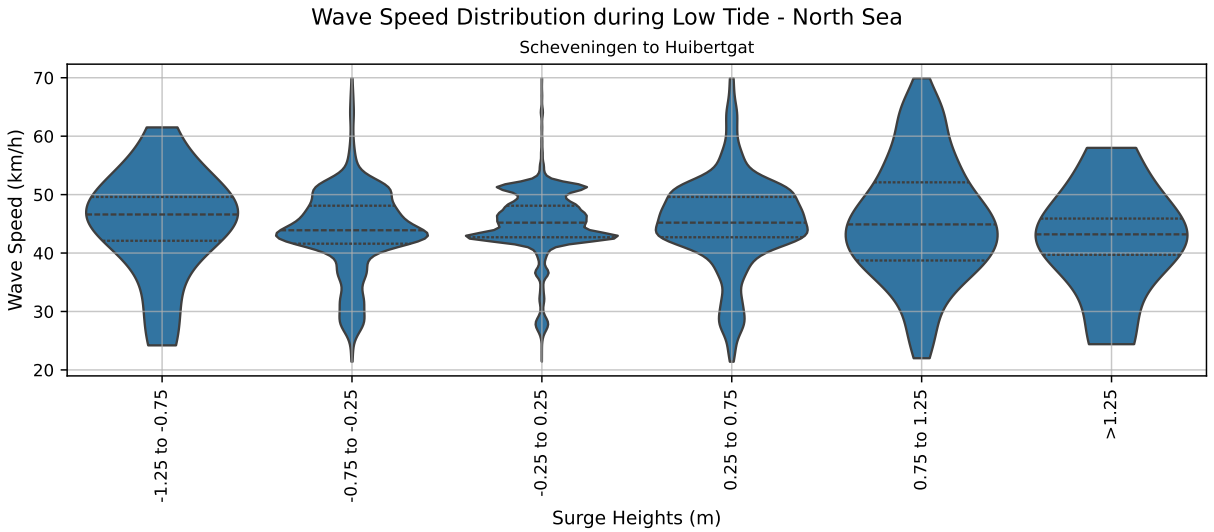
Region	Distance key	Storm1	Storm2	P-Value	Significant
Wadden Sea	Den Helder to Harlingen	-0.25 to 0.25	-1.25 to -0.75	0.033	True
Wadden Sea	Den Helder to Harlingen	-0.25 to 0.25	-0.75 to -0.25	0.000	True
Wadden Sea	Den Helder to Harlingen	-0.25 to 0.25	0.25 to 0.75	0.000	True
Wadden Sea	Den Helder to Harlingen	-0.25 to 0.25	0.75 to 1.25	0.000	True
Wadden Sea	Den Helder to Harlingen	-0.25 to 0.25	>1.25	0.000	True
Wadden Sea	Den Helder to Oudeschild	-0.25 to 0.25	-1.25 to -0.75	0.000	True
Wadden Sea	Den Helder to Oudeschild	-0.25 to 0.25	-0.75 to -0.25	0.000	True
Wadden Sea	Den Helder to Oudeschild	-0.25 to 0.25	0.25 to 0.75	0.000	True
Wadden Sea	Den Helder to Oudeschild	-0.25 to 0.25	0.75 to 1.25	0.000	True
Wadden Sea	Den Helder to Oudeschild	-0.25 to 0.25	>1.25	0.000	True
North Sea	Scheveningen to Huibertgat	-0.25 to 0.25	-1.25 to -0.75	0.177	False
North Sea	Scheveningen to Huibertgat	-0.25 to 0.25	-0.75 to -0.25	0.000	True
North Sea	Scheveningen to Huibertgat	-0.25 to 0.25	0.25 to 0.75	0.000	True
North Sea	Scheveningen to Huibertgat	-0.25 to 0.25	0.75 to 1.25	0.000	True
North Sea	Scheveningen to Huibertgat	-0.25 to 0.25	>1.25	0.000	True
Westerschelde	Vlissingen to Bath	-0.25 to 0.25	-1.25 to -0.75	0.518	False
Westerschelde	Vlissingen to Bath	-0.25 to 0.25	-0.75 to -0.25	0.006	True
Westerschelde	Vlissingen to Bath	-0.25 to 0.25	0.25 to 0.75	0.429	False
Westerschelde	Vlissingen to Bath	-0.25 to 0.25	0.75 to 1.25	0.130	False
Westerschelde	Vlissingen to Bath	-0.25 to 0.25	>1.25	0.190	False
Wadden Sea	Wierumergronden to Lauwersoog	-0.25 to 0.25	-1.25 to -0.75	0.000	True
Wadden Sea	Wierumergronden to Lauwersoog	-0.25 to 0.25	-0.75 to -0.25	0.000	True
Wadden Sea	Wierumergronden to Lauwersoog	-0.25 to 0.25	0.25 to 0.75	0.000	True
Wadden Sea	Wierumergronden to Lauwersoog	-0.25 to 0.25	0.75 to 1.25	0.000	True
Wadden Sea	Wierumergronden to Lauwersoog	-0.25 to 0.25	>1.25	0.267	False

Table 11: T-test between surges of the wave speeds during high tide. Here, all surge groups per location were compared with the -0.25 to 0.25 surge range. A p-value smaller than 0.05 indicates that the means of the wave speeds between the two surge groups are significantly different from one another.

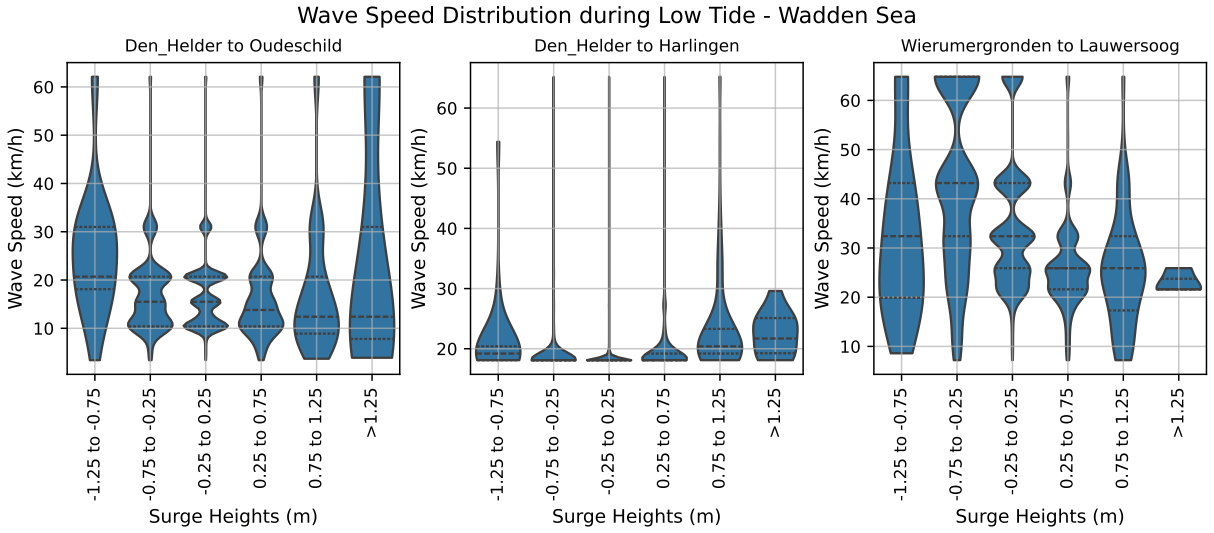
In figure 26, wave speeds distributions during low tide can be seen. In the North Sea (figure 26a) there are no large changes in wave speed with changing surges. The t-tests support that there are no significant changes in the wave speeds' means between different surge groups (tables 12 and 13). Therefore, in the North Sea during low tide, there is no significant correlation with wave speed and changing surge heights.

In the Wadden Sea (figure 26b), there is a downward shift from Den Helder to Oudeschild with increasing surge heights. We can see from the t-test with the -0.25 to 0.25 group that all these shifts are significant (table 13). When comparing with consecutive surges, we see that the last two groups do not change significantly from each other (table 13). We can therefore say that surges do affect the wave speed significantly, but for the larger surges, this change is not significant when compared with the previous surge from Den Helder to Oudeschild. From Den Helder to Harlingen, there are also small increases in wave speeds with larger surges. These changes are significant when comparing with the -0.25 to 0.25 group (table 13), however the >1.25 surges are not significantly different when compared with the 0.75 to 1.25 group. During low tide there is therefore a significant change in wave speed with changing surge heights from Den Helder to Harlingen. From Wierumergronden to Lauwersoog, there is a reduction in wave speed distribution with increasing surge heights. From the t-test with the -0.25 to 0.25 group we can see that this change is significant, except for the most negative and positive surges (table 13). When comparing with consecutive surges, the t-test showed that in the largest two surge groups there were no significantly changes. This means that surges do correlate with the decrease in wave speed we see, but only up to and including the 0.25 to 0.75 group from Wierumergronden to Lauwersoog.

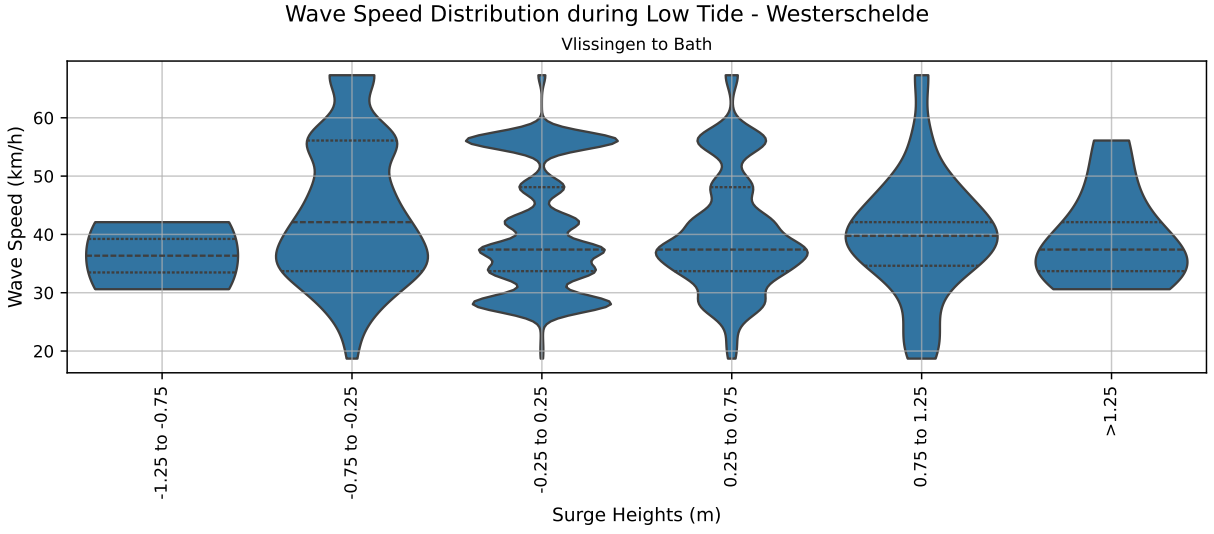
In the Westerschelde (figure 26c), we do see some changes in wave speed distributions with changing surge heights. From the t-test in table 13 we can see that only the -0.75 to -0.25 and 0.25 to 0.75 are significantly different from the -0.25 to 0.25 group. Table 12 reflects the same result. We can therefore say that in the Westerschelde, only smaller surges correlate significantly with the wave speed shifts we see.



(a) North Sea



(b) Wadden Sea



(c) Westerschelde

Figure 26: Wave speed distributions for the three studied regions during low tide. Note that the distributions are plotted, not the actual number of times a certain wave speed occurred.

Region	Distance key	Storm1	Storm2	P-Value	Significant
Wadden Sea	Den Helder to Harlingen	-1.25 to -0.75	-0.75 to -0.25	0.026	True
Wadden Sea	Den Helder to Harlingen	-0.75 to -0.25	-0.25 to 0.25	0.000	True
Wadden Sea	Den Helder to Harlingen	-0.25 to 0.25	0.25 to 0.75	0.000	True
Wadden Sea	Den Helder to Harlingen	0.25 to 0.75	0.75 to 1.25	0.000	True
Wadden Sea	Den Helder to Harlingen	0.75 to 1.25	>1.25	0.689	False
Wadden Sea	Den Helder to Oudeschild	-1.25 to -0.75	-0.75 to -0.25	0.000	True
Wadden Sea	Den Helder to Oudeschild	-0.75 to -0.25	-0.25 to 0.25	0.041	True
Wadden Sea	Den Helder to Oudeschild	-0.25 to 0.25	0.25 to 0.75	0.001	True
Wadden Sea	Den Helder to Oudeschild	0.25 to 0.75	0.75 to 1.25	0.134	False
Wadden Sea	Den Helder to Oudeschild	0.75 to 1.25	>1.25	0.058	False
North Sea	Scheveningen to Huibertgat	-1.25 to -0.75	-0.75 to -0.25	0.508	False
North Sea	Scheveningen to Huibertgat	-0.75 to -0.25	-0.25 to 0.25	0.000	True
North Sea	Scheveningen to Huibertgat	-0.25 to 0.25	0.25 to 0.75	0.217	False
North Sea	Scheveningen to Huibertgat	0.25 to 0.75	0.75 to 1.25	0.759	False
North Sea	Scheveningen to Huibertgat	0.75 to 1.25	>1.25	0.267	False
Westerschelde	Vlissingen to Bath	-1.25 to -0.75	-0.75 to -0.25	0.383	False
Westerschelde	Vlissingen to Bath	-0.75 to -0.25	-0.25 to 0.25	0.000	True
Westerschelde	Vlissingen to Bath	-0.25 to 0.25	0.25 to 0.75	0.045	True
Westerschelde	Vlissingen to Bath	0.25 to 0.75	0.75 to 1.25	0.828	False
Westerschelde	Vlissingen to Bath	0.75 to 1.25	>1.25	0.852	False
Wadden Sea	Wierumergronden to Lauwersoog	-1.25 to -0.75	-0.75 to -0.25	0.002	True
Wadden Sea	Wierumergronden to Lauwersoog	-0.75 to -0.25	-0.25 to 0.25	0.000	True
Wadden Sea	Wierumergronden to Lauwersoog	-0.25 to 0.25	0.25 to 0.75	0.000	True
Wadden Sea	Wierumergronden to Lauwersoog	0.25 to 0.75	0.75 to 1.25	0.399	False
Wadden Sea	Wierumergronden to Lauwersoog	0.75 to 1.25	>1.25	0.742	False

Table 12: T-test between surges of the wave speeds during low tide. Here, each surge group is compared with the previous surge group. A p-value smaller than 0.05 indicates that the means of the time differences between two surges are significantly different from one another.

Region	Distance key	Storm1	Storm2	P-Value	Significant
Wadden Sea	Den Helder to Harlingen	-0.25 to 0.25	-1.25 to -0.75	0.000	True
Wadden Sea	Den Helder to Harlingen	-0.25 to 0.25	-0.75 to -0.25	0.000	True
Wadden Sea	Den Helder to Harlingen	-0.25 to 0.25	0.25 to 0.75	0.000	True
Wadden Sea	Den Helder to Harlingen	-0.25 to 0.25	0.75 to 1.25	0.000	True
Wadden Sea	Den Helder to Harlingen	-0.25 to 0.25	>1.25	0.000	True
Wadden Sea	Den Helder to Oudeschild	-0.25 to 0.25	-1.25 to -0.75	0.000	True
Wadden Sea	Den Helder to Oudeschild	-0.25 to 0.25	-0.75 to -0.25	0.041	True
Wadden Sea	Den Helder to Oudeschild	-0.25 to 0.25	0.25 to 0.75	0.001	True
Wadden Sea	Den Helder to Oudeschild	-0.25 to 0.25	0.75 to 1.25	0.291	False
Wadden Sea	Den Helder to Oudeschild	-0.25 to 0.25	>1.25	0.000	True
North Sea	Scheveningen to Huibertgat	-0.25 to 0.25	-1.25 to -0.75	0.849	False
North Sea	Scheveningen to Huibertgat	-0.25 to 0.25	-0.75 to -0.25	0.000	True
North Sea	Scheveningen to Huibertgat	-0.25 to 0.25	0.25 to 0.75	0.217	False
North Sea	Scheveningen to Huibertgat	-0.25 to 0.25	0.75 to 1.25	0.447	False
North Sea	Scheveningen to Huibertgat	-0.25 to 0.25	>1.25	0.055	False
Westerschelde	Vlissingen to Bath	-0.25 to 0.25	-1.25 to -0.75	0.577	False
Westerschelde	Vlissingen to Bath	-0.25 to 0.25	-0.75 to -0.25	0.000	True
Westerschelde	Vlissingen to Bath	-0.25 to 0.25	0.25 to 0.75	0.045	True
Westerschelde	Vlissingen to Bath	-0.25 to 0.25	0.75 to 1.25	0.514	False
Westerschelde	Vlissingen to Bath	-0.25 to 0.25	>1.25	0.701	False
Wadden Sea	Wierumergronden to Lauwersoog	-0.25 to 0.25	-1.25 to -0.75	0.268	False
Wadden Sea	Wierumergronden to Lauwersoog	-0.25 to 0.25	-0.75 to -0.25	0.000	True
Wadden Sea	Wierumergronden to Lauwersoog	-0.25 to 0.25	0.25 to 0.75	0.000	True
Wadden Sea	Wierumergronden to Lauwersoog	-0.25 to 0.25	0.75 to 1.25	0.000	True
Wadden Sea	Wierumergronden to Lauwersoog	-0.25 to 0.25	>1.25	0.124	False

Table 13: T-test between surges of the wave speeds during low tide. Here, all surge groups per location were compared with the -0.25 to 0.25 surge range. A p-value smaller than 0.05 indicates that the means of the wave speeds between the two surge groups are significantly different from one another.

4 Discussion

In this study several tide-surge interactions for different regions along the Dutch coast were investigated, namely: the surge influence on the observed water level and tidal range, the surge effect on the timing difference of the observed WL compared with the astronomic WL and the surge effect on the wave speed.

One thing is clear: higher surges lead to higher water levels. This was shown at all locations. However the surge's influence differs from location to location and from region to region. Pousa et al. (2013) already showed that surges from one location to another could be vastly different. In the three regions studied, we do see differences on the influence surge has on the observed WL, though less extreme. Given that the tide behaves differently in the Westerschelde and Wadden Sea compared to the North Sea, it is not strange to see that the impact of the surge is also generally stronger in the Westerschelde and Wadden Sea than in the North Sea. The most likely reason for this is that both the Westerschelde and Wadden Sea are relatively shallow areas, compared to the North Sea, which is in line with findings of Feng et al. (2021). The surge therefore experiences more varying frictions and depths, leading to similar deformations as the tide. Given that Wang et al. (2019) showed that the tide in the Westerschelde increases landward up to 100-120km into the estuary, the results of figure 19 can likely be explained that the surge tends to increase as well. However, as we see at Bath, the slope decreases around the Belgian border. It is possible that, the river discharge becomes a large enough factor for the surge to influence the tide even further, as surges can be changed due to river discharge (Plüß et al., 2001). For future research, given the different periods and categories of storm surges (Bui, 2021), it can be interesting to look if the duration of a surge has influence on how strong the influence of the surge is on the observed water level. For example, if a 0.5m surge last only a couple hours versus a 0.5m surge that last a full day, does that change the effect on the observed water level?

It is likely, given the results in figure 20 and figure 21, that storm surges have little impact on the tidal range. Only in the Westerschelde the tidal range seems to have a visible trend upwards as storms get larger. This could be explained by the fact that further into the estuary, the average water depth decreases, and as stated by van Rijn (2010) between a water depth of 7 and 11m, the tidal range tends to increase if the water depth increases further. In their case they were modeling the effect of dredging on the tidal range, thus a more permanent situation than a storm surge. Nevertheless, a short increase in water depth could then temporarily increase the tidal range ever so

slightly. Given the result that the observed WL in the Westerschelde increases more due to the surge further into the Estuary, we can say with caution that surges in the Westerschelde tend to increase the tidal range. We also see for Scheveningen and IJmuiden there is some correlation between larger surges and larger tidal range. Looking at figures 4 and 5 we can see that the locations with the slightly larger fit have in common that they are positioned relatively close to the Southern amphidromic point, whereas the Wadden Sea and Wadden Islands data points are more linked with the center amphidromic point. Given that we know from D. Pugh and Woodworth (2014) that the further away from an amphidromic point the tidal range increases, an increase in surge should lead to a amphidromic point shift resulting in larger tidal ranges. However, if the distance to the center amphidromic point is already large, a storm surge might result in a relatively minor shift of that point. In contrast, the shorter distance to the southern amphidromic point could lead to a relatively larger shift of its position. If this is the case, that would explain the pattern we see for the Westerschelde, Scheveningen and IJmuiden. A model study to see the evolution of the amphidromic points system due to surges in the North Sea could help explain these results. Furthermore, such a study could help identify if the Southern amphidromic point is more susceptible to changes, and might therefore be less stable. Another approach could be to expand this study and take data along the whole North Sea (from England, to Norway) and map the amphidromic point system during storms. Still, we do see large scatter within the locations that do show some fit. From a model study by Lewis et al. (2017) we can see in figure 27 what happens to the tidal signal when a storm surge occurs. We see that both the high and low tide shift down or up accordingly with a negative or positive surge. Given this, the tidal range deforms little if at all, if the increase or decrease in the same for high and low tide. Due to time constraints, this research did not look at the effects of wind direction and the effect of wind on surges, but this could have a large influence. Future research might look further into the effects of wind on the tide-surge interactions. Given that the tide generally tends to stay within a single inlet basin in the Wadden Sea (Stanev et al., 2003), large surges could result the tide overflowing from one basin to another during high tide. This would cause the waves to have a whole other interaction between the basins, which could also explain the large scatter. A further investigation on the tidal range due to surges in the Wadden Sea is recommended.

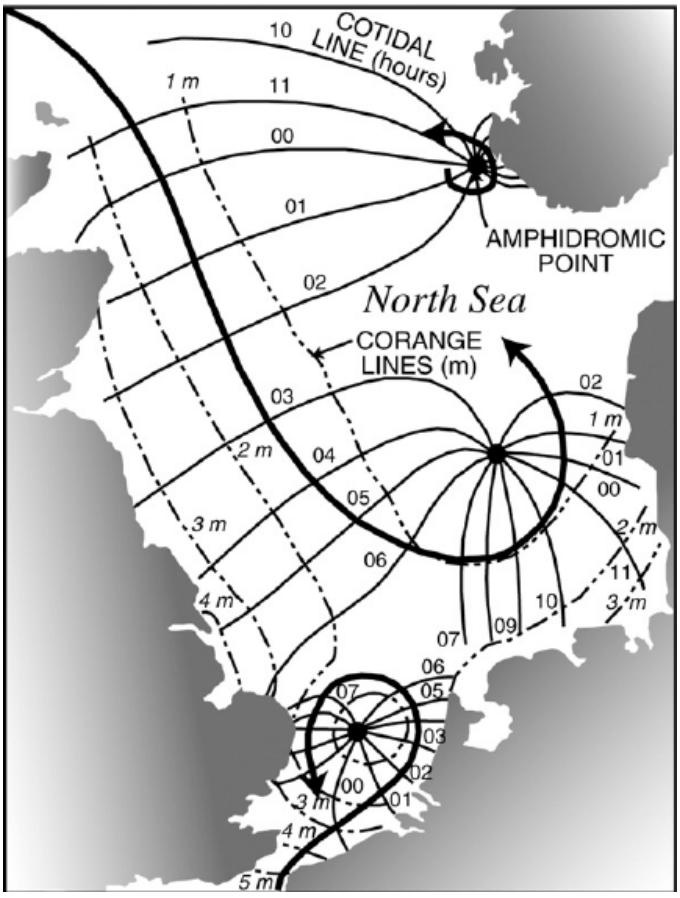


Figure 4 repeat: Amphidromic points in the North Sea. Dotted lines are the co-tidal range lines, the filled lines are co-tidal phase lines. Figure source: Kvale (2006).

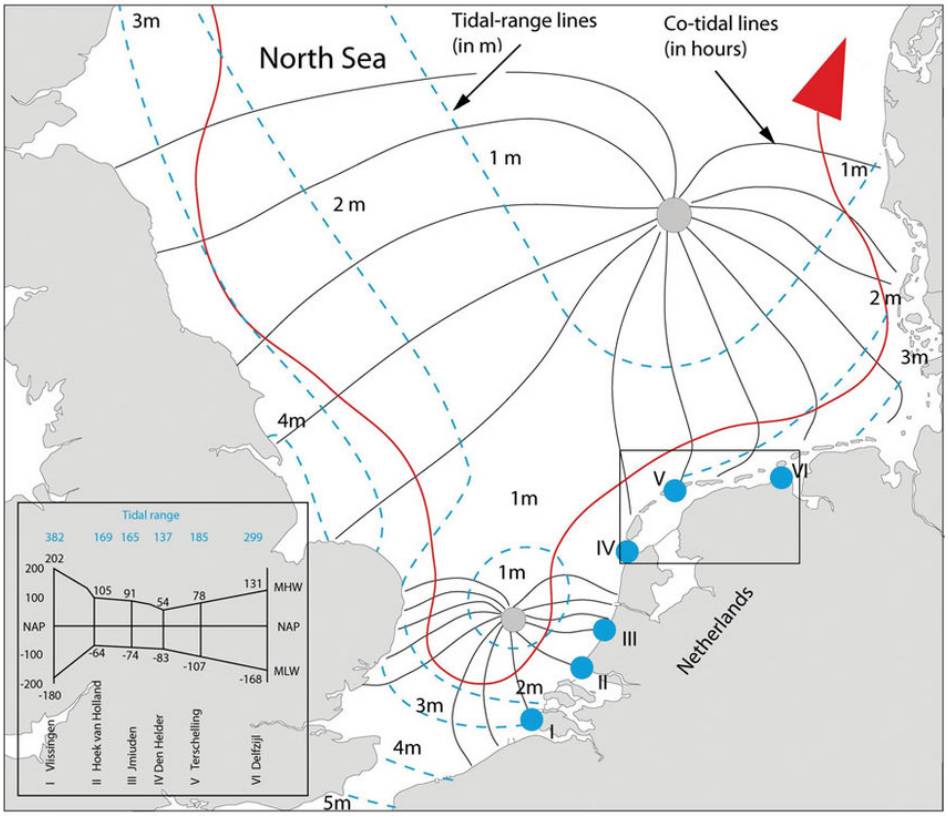


Figure 5 repeat: Tidal wave propegation through the North Sea. Figure source: Vos and Knol (2015).

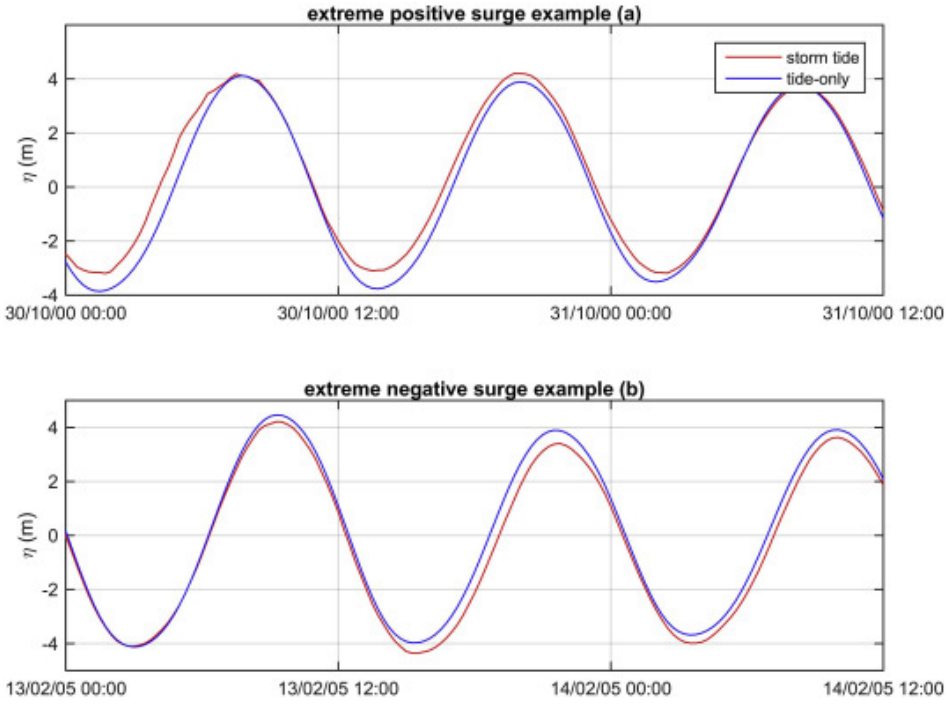


Figure 27: Example of the tidal range evolution during a storm surge. Figure source: Lewis et al. (2017).

Timing of the high and low tide seem for the most part to coincide with similar changes in wave speeds. The exception here is in the Westerschelde, where both high and low tide wave speeds do not change much with changing surge heights. The insensitivity of wave speed changes to surge height during high tide can be attributed to the presence of intertidal mudflats in the Westerschelde. During spring tide these mudflats flood, which cause the average water depth to decrease, therefore creating lower wave speeds (see figure 13) (Schepers et al., 2018). During high

tide, in the Westerschelde, the mudflats get flooded with larger surges even when it is not spring tide, which causes a stop for the water depth increase, and therefore a control on the wave speed. During low tide this is unexpected, as Rossiter (1961), Horsburgh and Wilson (2007), and Feng et al. (2021) showed that shallow seas and estuaries are more susceptible to changes in water depth for the wave speed. Wave speed is controlled by water depth, given by equation $c = \sqrt{gh}$. However, during low tide we also do not see significant changes in wave speed for different surge heights. Though we do visually see a small increase in wave speeds in the 0.75 to 1.25 surge group, the t-test still results in that this is not a significant change. Looking into how many data points are in the datasets for these groups, we see that the number of points for the more extreme surge groups are much lower than the little to no surge group. Given that the t-test is also taking the number of data points into account, this could explain the results. This could happen when the code is looking for peaks within certain time interval, but sometimes, there are no such peaks available. The find peaks function in Python is not without limitations, and despite thorough checks, it is possible that critical peaks are still overlooked. This can result in gaps between the peaks of Vlissingen and Bath that too far apart. With more time this peak function should be perfected, so that these incidences do not happen. However, looking at other locations, the number calculated wave speeds is large enough, so the peak finding might not be perfect, but sufficient in most cases. It has been stated by Smolders et al. (2015) wetlands of different elevations and sizes attenuate different moments in the tidal cycle. Perhaps these differently elevated areas control different surge heights as well, which could explain the little changes we see. The timing of high and low tide in the Westerschelde is significant, however. If wave speed is not the cause, this can come from increased non-linearity in the tide-surge interaction, where the surge can precede 3-5 hours of peak WL (Horsburgh & Wilson, 2007). Also given the results of the surge having a stronger influence on water levels in the Westerschelde than in the North Sea (figure 19), it is possible that this non-linearity is also stronger in the Westerschelde. In any case, further research into the effects of wave speed changes due to surge and intertidal mudflats in the Westerschelde is necessary to better understand what is happening in the Westerschelde estuary.

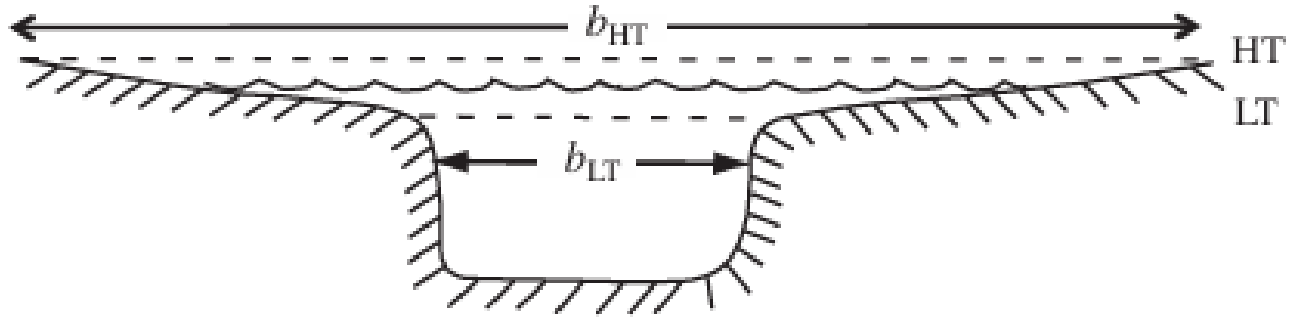


Figure 13 repeat: Schematic cross-sectional overview intertidal mudflats flooding control on wave speeds. When the tidal wave only travels through the channel at width b_{LT}, any water on top directly increases the water depth and thus the wave speed. However, at b_{HT} when the intertidal mud flats get flooded, the average depth decreases due to the larger area. Figure source: Pethick (1980).

The changes in timing in the North Sea during high tide, where significant, nicely correlate with the wave speed changes during high tide. This is likely directly correlated with the equation for the wave speed, where a change in water depth due to surge alters the wave speed. During low tide, the changes in wave speed are not significant, and therefore there is no correlation between surge height and wave speed during low tide. Again, during low tide, the timing changes are then likely due to the increased non-linearity of the tide-surge interaction.

In the Wadden Sea we see that significant time difference shifts for varying surge heights, share a similar pattern with the shifts in wave speeds for varying surge heights. This is true for both high and low tide. Both the significant and non significant shifts can here be explained by the existence of the intertidal areas. Given that the Wadden Sea is a shallow sea, it is very sensitive for small water level changes (De Jonge et al., 1993). This is nicely reflected at Harlingen, a location in the Wadden Sea with little intertidal areas (see figures 10 and 11). The lack of intertidal areas at Harlingen, means that any change in water level should reflect the changes in wave speed and the timing difference, which is what we see in the results. The surges impact on flooding or exposing of intertidal areas, is nicely reflected at locations like Lauwersoog, where we see that the wave speed and time difference shifts reflect the response of the tide due to the surge influence, resulting in flooded or exposed intertidal areas. From Lauwersoog, we can see that these locations are more susceptible to changes of the surge during high tide, as intertidal areas are already flooded, therefore leading to faster wave speeds and earlier high tide. During low tide we then see little changes in time difference and wave speed, as then, the intertidal areas are exposed, and larger surges cause flooding

of these areas, therefore the water depth does not increase further. Locations like Oudeschild are situated more with less intertidal areas, but some are still present. Here, with larger surges during high tide, the intertidal areas get flooded and therefore increasing wave speed and causing earlier high tide. With a negative surge, these area can get exposed again, leading to an increase in depth due to the main channel now being the only way for the tide to travel through. During low tide, locations like Oudeschild will have exposed intertidal areas, and as soon as they get flooded due to the effects of the surge, the water depth does not change much, therefore leading to little to no change in wave speed and timing.

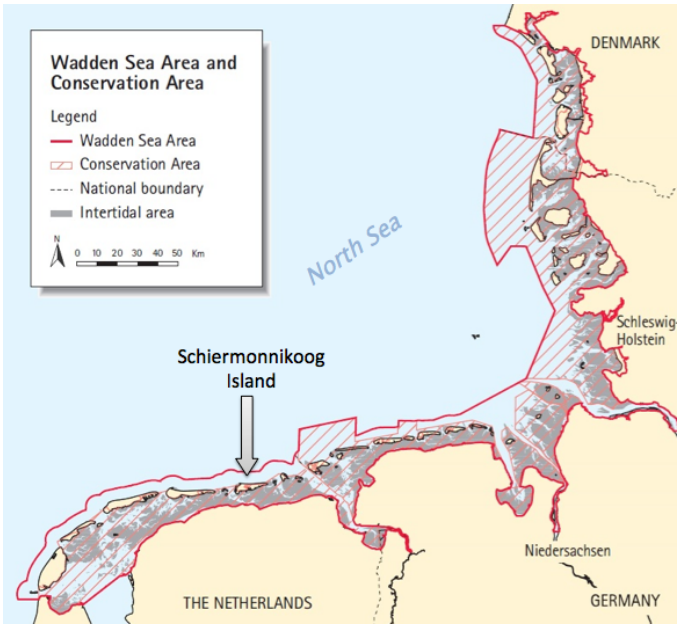


Figure 10 repeat: Wadden Sea Intertidal Areas. Figure source: "Common Wadden Sea Secretariat — Wadden Sea" (n.d.).

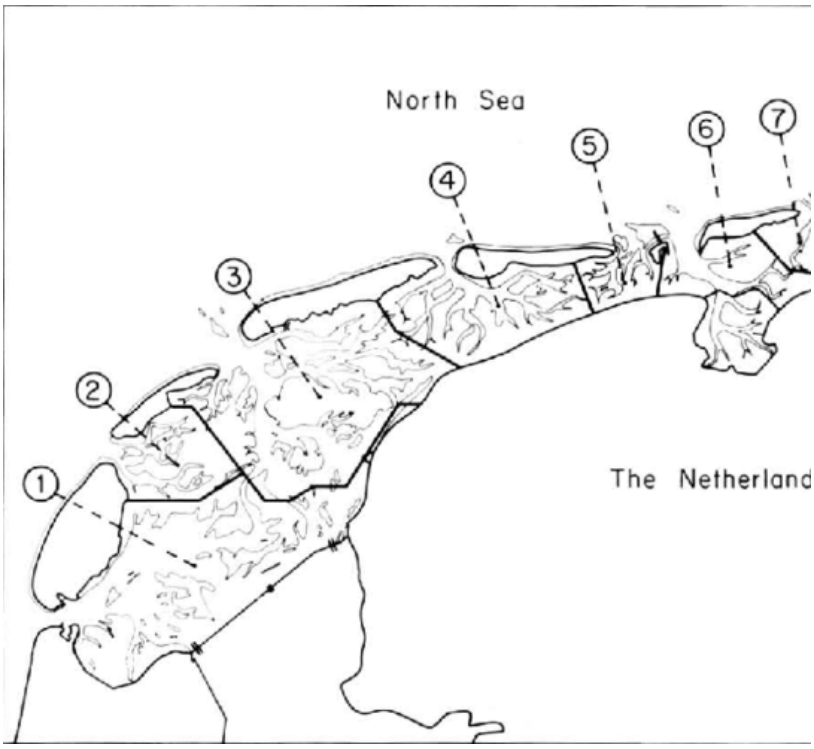


Figure 11 repeat: Tidal basins of the Wadden Sea. The black lines indicate the boundaries of where the tide goes. Every inlet therefore has its own tidal basin. The grey lines show where the intertidal areas are present. Figure source: Bergman et al. (1989).

5 Conclusion

Tide-surge interaction in the Dutch North Sea have different strengths between the regions and locations on the observed WL. In the Wadden Sea and Westerschelde, the surge effect on the peak water level is significantly larger than along the North Sea coast. Also within the Wadden Sea, basins determine the strength of the tide-surge interaction on the observed WL. In the Westerschelde, up to Bath, the influence of the surge on the observed WL increases.

There is no correlation between the tidal range in the Wadden Sea, likely due to basin overflow. Another factor might be the distance from the amphidromic points in the North Sea, as small changes far away can have less influences than small changes relatively near an amphidromic point. Only the tidal range at Scheveningen, IJmuiden and the Westerschelde have a small correlation, perhaps due to the relatively nearby Southern amphidromic point. Future research here is needed.

Results show that the full tidal cycle is not significantly shifted due to surges. Only during low or high tide do we see significant changes, but this is dependant on the location. Sometimes this can be connected with the wave speed, as is often the case within the Wadden Sea. Often the results can be connected due to the presence of intertidal areas or mudflats.

Generally the tidal wave speeds increase due to the effect of larger surges. However this is dependent on several factors: low or high tide, presence of intertidal areas, and the region/location. The Westerschelde clearly shows little to no effect in wave speed due to surges, whereas the North Sea and Wadden Sea do.

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